THE OHIO JOURNAL OF SCIENCE

Vol. 70 | JANUARY, 1970 | No. 1

THE BASS ISLANDS FORMATION IN ITS TYPE REGION[1, 2]

DALE R. SPARLING

Southwest Minnesota State College, Marshall, Minnesota

ABSTRACT

The Upper Silurian Bass Islands Formation has as its type region the Bass Islands, of Ottawa County, Ohio. Originally divided into the Greenfield, Tymochtee, Put-in-Bay, and Raisin River subunits, it has been classed as a series, group, and formation by different workers, and has been redefined, restricted, and even eliminated in the subsurface by others. The Bass Islands is here considered to be a formation, divisible, in the type region, into the four members listed above. The formation, which consists entirely of hypersaline facies, disconformably overlies the marine Lockport ("Guelph") Dolomite and is separated from the overlying Amherstburg Dolomite by the Tippecanoe-Kaskaskia unconformity.

The Greenfield Member consists of about 110 feet of dolomite lacking in argillaceous matter. It is equivalent to the A_1 unit of the Salina of subsurface terminology, and a widespread disconformity at its top corresponds to the "Newburg" zone of the subsurface.

The Tymochtee Member comprises about 560 feet of dolomite, anhydrite, gypsum, and shale which correspond to the A_2 and other lettered subdivisions of the Salina.

Disconformably overlying the Tymochtee are about 80 feet of dolomite forming the Put-in-Bay and Raisin River members, which can be differentiated (by degree of brecciation) only in the Lake Erie islands. Brecciated units characterize the Put-in-Bay, and breccias locally occupy channels cut into the upper part of the Tymochtee. The Raisin River is characterized by more limited brecciation and by pseudobreccias.

The paleogeographic setting and association with penesaline facies suggest that most carbonates of the Bass Islands Formation have been dolomitized by seepage refluxion prior to final lithification.

INTRODUCTION

During the course of a study of the bedrock geology of Ottawa County, Ohio, the Upper Silurian Bass Islands stratigraphic unit was studied in considerable detail. The county includes the Bass Islands, which are nominally the type region of the stratigraphic unit, although only one of its subdivisions, the Put-in-Bay Dolomite, has its type section in the islands. The major purpose of this paper is to define precisely the unit and its subunits, including petrographic distinctions and the nature of the contacts. Also considered are the sedimentary and diagenetic environments. An additional aim is to present the writer's interpretation of the stratigraphic correlation of the Upper Silurian of this region with that of adjacent regions.

Ottawa County lies in the northern part of the Findlay Arch region (fig. 1). As seen on the geologic map, the Bass Islands unit swings around the northward-plunging nose of the arch and overlies dolomites of the Lockport Group which crop out along its axis. The term Lockport as used here includes dolomites designated Guelph by some workers. However, the Guelph stratigraphic unit was originally differentiated from the Lockport—as the "Galt limestone" by

[1]Taken from part of a dissertation submitted to the Graduate School of Ohio State University in partial fulfillment of the requirements for the degree of Doctor of Philosophy.

[2]Manuscript received March 24, 1968.

Hall (1852, p. 340–341) and as the Guelph formation by Logan (1863, p. 336–344)—because the fossil assemblage of the Guelph differs from that of the Lockport in its type region. The Guelph is therefore a biostratigraphic unit in terms of modern classification, and usage of the term in the Findlay Arch region has never involved precise definition, even as a faunal zone. The term Lockport was originally applied to strata immediately beneath the red shales of the "saliferous group" (Hall, 1839, p. 289), which are the lowermost Upper Silurian strata (Vernon Shale) in New York State. This relationship, together with its priority over the term Guelph, makes the Lockport a suitable name for the equivalent strata in the Findlay Arch region.

The contact between the Lockport and the Bass Islands in western Ottawa County is unconformable, but this condition may well be restricted to the axial portion of the Findlay Arch. An interregional unconformity at the top of the Bass Islands marks its boundary with the Middle Devonian Detroit River Group.

HISTORY OF THE NOMENCLATURE

The Bass Islands unit of Ottawa county consists of about 750 feet of strata deposited under hypersaline conditions. It is subdivisible into three distinct units—a lower dolomite (Greenfield), a middle unit consisting largely of shaly and argillaceous penesaline evaporites (Tymochtee), and an upper dolomite (Put-in-Bay and Raisin River members). The lower and upper dolomites bear a superficial resemblance to each other, a fact that has caused considerable confusion.

The development of the nomenclature is outlined in Figure 2. The earliest classification of Upper Silurian strata of Ottawa County was that of Newberry (1870), who studied exposures in the eastern part of the county. The upper part of the shaly evaporite-bearing sequence was identified as being equivalent to the Salina of New York, and the overlying dolomites were classed as the "Waterlime" of the New York classification, on the basis of lithologic similarity and the presence of fossils of the large ostracode genus *Leperditia*.

Winchell later (1874) studied the Greenfield near Genoa, in western Ottawa County, and considered it to be equivalent to the "Waterlime" overlying the Salina of Newberry to the east. This misidentification of the upper and lower dolomites is understandable in view of the fact that fossil molds of *Leperditia* are common in both units. Because the "Waterlime" in New York was separated from the Lockport by the Salina, Winchell assumed that the Salina near Genoa was reduced to less than a foot of green shale just above the Lockport. Actually this thin shale is the basal Greenfield, which in turn is separated from the "Waterlime" by over 550 feet of strata.

The fact that the Salina of Newberry is sandwiched between the upper and lower dolomite units was not recognized until cuttings from a well drilled at Sandusky in 1886 were studied by Orton (1888, p. 194). Orton apparently realized that the dolomite (Greenfield) beneath the thick gypsum-bearing sequence, called Salina by Newberry, was the same unit that Winchell had described near Genoa. It followed that the Salina was not equivalent to the thin shale at Genoa, nor was the dolomite there equivalent to the "Waterlime" of the eastern part of the county. However, instead of considering the lower dolomite to lie below the Salina, Orton considered the entire Upper Silurian sequence to be equivalent to the "Waterlime" of the New York classification, largely because of the existence of *Leperditia* directly above the Lockport at Genoa (1888a, p. 697). The Salina, which underlies the "Waterlime" in New York, was considered by Orton to be missing in the Findlay Arch region. The effects of this misidentification were long-lasting.

The next classification of the Upper Silurian of this region was made by geologists of the Michigan Geological Survey. Lane (1895, p. 26–28) proposed the term "Monroe beds" for all strata from the base of the Dundee (Middle Devonian) ". . . down to the lowest gypsiferous beds," thus including strata now classed as

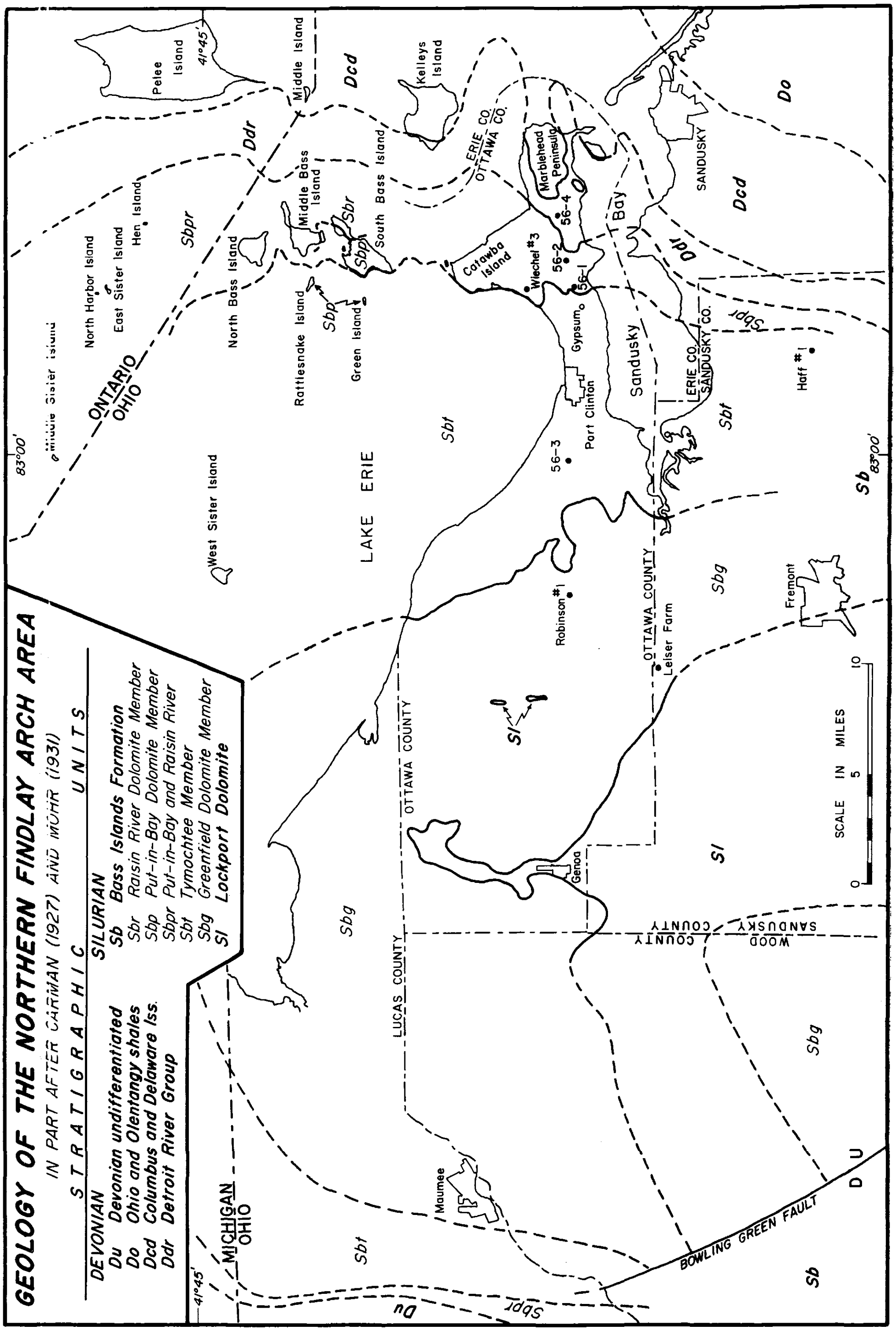


FIGURE 1. Geologic map of the northern Findlay Arch region showing locations of various areas referred to in the text.

Salina in the Michigan Basin. The type region of the "Monroe" was Monroe County, southeastern Michigan. The Silurian part of this unit was subsequently termed the "Lower Monroe," and Grabau (1908) restricted it to exclude the Salina.

The Lower Monroe was renamed the "Bass Islands series" (Lane, Prosser, Sherzer, and Grabau, 1909), nominally for strata exposed on the Bass Islands of Ottawa County. The Bass Islands unit was defined as containing four subdivisions—the Greenfield dolomite, the Tymochtee shales and limestones, the Put-in-Bay dolomites, and the Raisin River dolomites.

The Greenfield had originally been named by Orton (1871, p. 289–291) for exposures around the town of Greenfield, in southwestern Ohio. The unit was first recognized in northern Ohio by Sherzer and Grabau (1909, p. 545), who cited its occurrence just south of Fremont, in Sandusky County. The type section of the Tymochtee is along Tymochtee Creek in northern Wyandot County, about 35 miles south of Ottawa County. Winchell (1873, p. 633) described about 85 feet of "Waterlime" strata cropping out along the creek, and designated 24 feet in the lower portion the "Tymochtee Slate." The original designation was misrepresented by Lane, Prosser, Sherzer, and Grabau (1909, p. 554), who claimed that Winchell had proposed the name for all the strata exposed along Tymochtee Creek. The thickness even grew in the telling to "something over a hundred feet." The Put-in-Bay and Raisin River units were named by Sherzer and Grabau (1909) for dolomite strata exposed on South Bass Island and in Monroe County, Michigan.

The Put-in-Bay and Raisin River dolomites are at least partly equivalent to the "Waterlime" as defined by Newberry, and to the "Lower Monroe" as redefined by Grabau in 1908. However, the Greenfield and Tymochtee are stratigraphically equivalent to part of the Salina of the Michigan Basin. Thus, in view of Grabau's (1908) restriction, the original definition of the Bass Islands (or Lower Monroe) was self-contradictory. As used in Ohio, the classification of 1909 was adaptable only because of Orton's earlier miscorrelation of all Upper Silurian strata in the Findlay Arch region with the post-Salina "Waterlime" and the acceptance of this error by Grabau and Sherzer (1910, p. 17). This misidentification also allowed usage of the term Tymochtee in the Bass Islands type region for the Salina, in spite of the latter's priority. The miscorrelation with New York was perpetuated until as late as 1942 by Cumings, Ehlers, and Foerste (*in* Swartz, 1942).

The first critical evaluation of the interrelationships among the subdivisions of the Bass Islands stratigraphic unit was made by Carman (1927), who used the term Bass Island (*sic*) for a formation within the Monroe "division," and treated the four subdivisions as members. Carman indicated that it was difficult to identify these members everywhere on the basis of lithologic characteristics. He was unable to locate the top of the Greenfield, but assigned all shaly strata above the Greenfield to the Tymochtee. The contact between the Tymochtee and Put-in-Bay members was found to be easily defined in Lucas and Ottawa counties, but obscure elsewhere. Carman also found that the Put-in-Bay could not be lithologically differentiated from the Raisin River Member to the south of the Findlay Arch region. The classification used by Carman was applied by Mohr (1931) to strata in the Bass Islands.

Stout (1941, table facing p. 46) referred to the Upper Silurian as the Bass Island group, divided into formations, even though he did not differentiate the formations consistently in extensive field studies in western Ohio. Stout recognized the equivalence of the lower part of the Bass Islands to the Salina of New York.

Alling and Briggs (1961, table 1) essentially followed the classification used by Stout. However, they pointed out the fact that the Tymochtee as originally defined is equivalent to only a small segment of the Salina of subsurface usage (p. 524–525). They also indicated that correlation of the Greenfield and Tymochtee with the Salina was uncertain at that time.

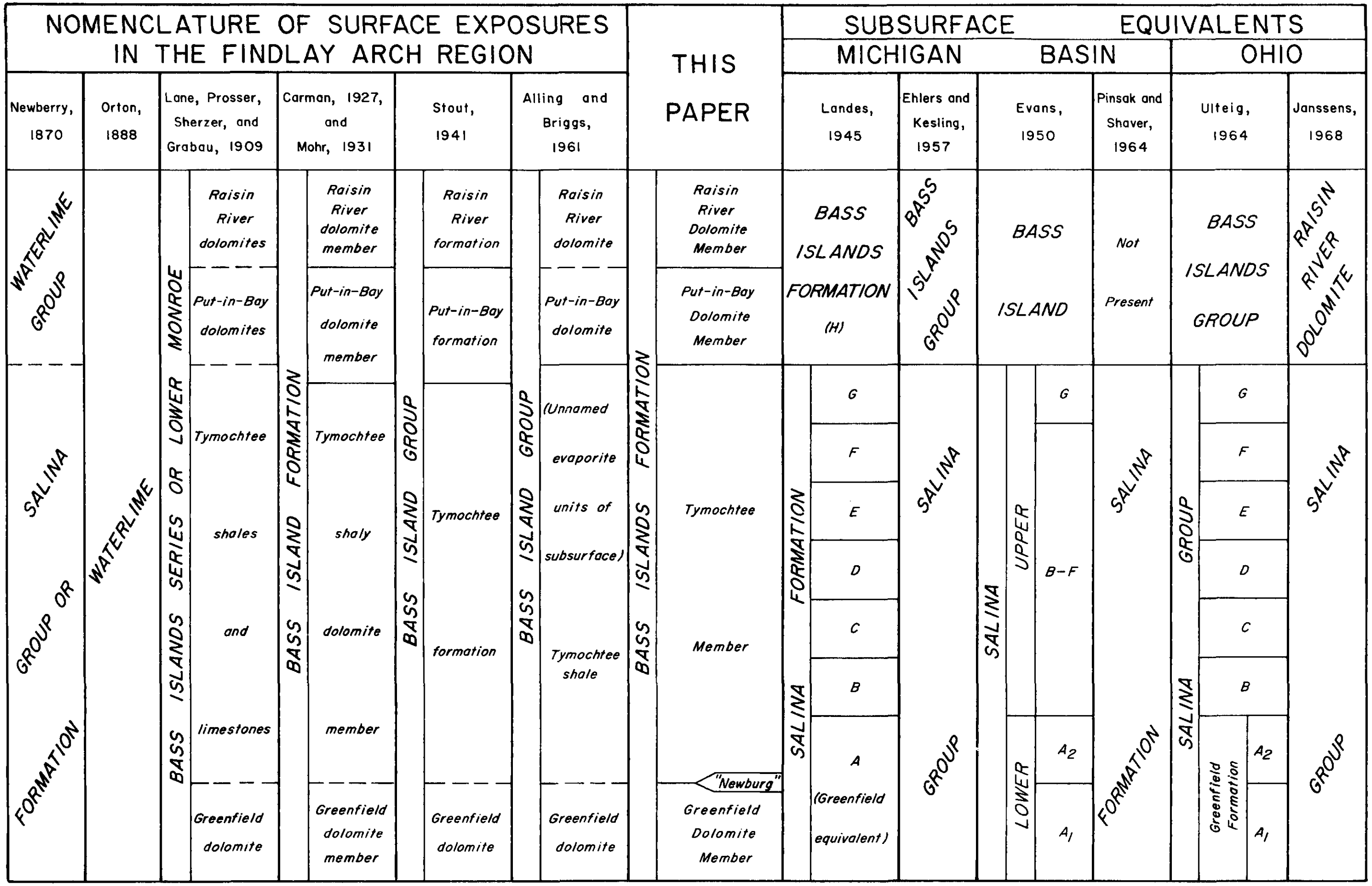


FIGURE 2. Development of Upper Silurian nomenclature in the Findlay Arch region, and lateral equivalents in the subsurface. Dashed lines indicate contacts not precisely defined in the Findlay Arch region.

A separate classification has developed in the subsurface. Landes (1945) divided the Upper Silurian of the Michigan Basin into the Salina and Bass Islands formations, and also into informal lettered units as shown in figure 2. Unit A was considered equivalent to the Greenfield. Evans (1950, p. 59) later subdivided the A unit in Ontario into lower and upper segments (A_1 and A_2), separated by a pronounced unconformity. Ehlers and Kesling (1957) treated the Salina and Bass Islands units as groups, but the Salina of the subsurface in Indiana was considered to be of formation status by Pinsak and Shaver (1964, p. 47).

The lettered units of the Michigan Basin were traced into the Appalachian Basin in Ohio by Ulteig (1964, p. 19), who indicated the Greenfield to be equivalent to the A_1 and A_2. Janssens (1968, p. 8) eliminated the Bass Islands unit entirely from the subsurface nomenclature by substituting the term Raisin River Dolomite for all strata above the Salina; the Put-in-Bay was considered to be a local facies of the Raisin River. This classification is presently accepted by the Ohio Geological Survey for both surface and subsurface usage (Horace Collins, personal communication, 1969). In view of the fact that all previous workers have considered the Raisin River to be a subunit of the Bass Islands, the writer feels that this redefinition and reclassification is unnecessary and unwarranted.

Although the subdivision of the Upper Silurian into two major units (Salina and Bass Islands) is generally applicable in the subsurface, the writer feels that the classification used by Carman in 1927 is more realistic for surface exposures and for the subsurface of some basin-margin areas in Ohio. By pointing out the difficulty of differentiating the subdivisions in outcrops, Carman established valid reasons for considering the Bass Islands unit to be of formation rank. Horvath (1964) found precise differentiation to be very difficult in the subsurface of central and southern Ohio, so the need for a single mapping unit having formation status is not restricted to surface exposures. Accordingly, the classification chosen for this paper is essentially that used by Carman, with the exception that the top of the Tymochtee is redefined for reasons given below.

THE BASS ISLANDS FORMATION AND ITS MEMBERS

Study of the Upper Silurian of the Ottawa County region involved examination of cores furnished by the United States Gypsum Company, well samples, and outcrops. Surface exposures are limited vertically, so the cores were valuable in differentiating the stratigraphic units and determining precise thicknesses. The nature of the Bass Islands Formation and its members as determined in cores from eastern Ottawa County is shown in Figure 3. Core 56–3 is the only one penetrating the entire Greenfield Dolomite Member, but the top of the Greenfield was correlated with the corresponding horizon in core 56–1 on the basis of several intervening control points. The remainder of the Bass Islands Formation is shown in a composite of cores 56–1, 56–2, and 56–4 at the position of 56–4. Overlapping sections of these cores are extremely easy to correlate bed for bed; it is possible to trace shale beds that are as thin as one inch.

Petrographic study involved examination, by binocular microscope, of cores, specimens from the field, and well samples. Polished sections of the various lithologic varieties encountered were useful in studying sedimentary structures and diagenesis. In the petrographic descriptions below, the following textural classification is employed for the carbonate rocks:

Grain Size	*Textural Term*
¼–½ mm	medium-grained
⅛–¼ mm	fine-grained
1/16–⅛ mm	very fine-grained
Granular but less than 1/16 mm	microgranular
No visible granularity	sublithographic

The average grain size of carbonates, which is very useful in differentiating the Bass Islands Formation and its members in the subsurface, is shown graphically in figure 3.

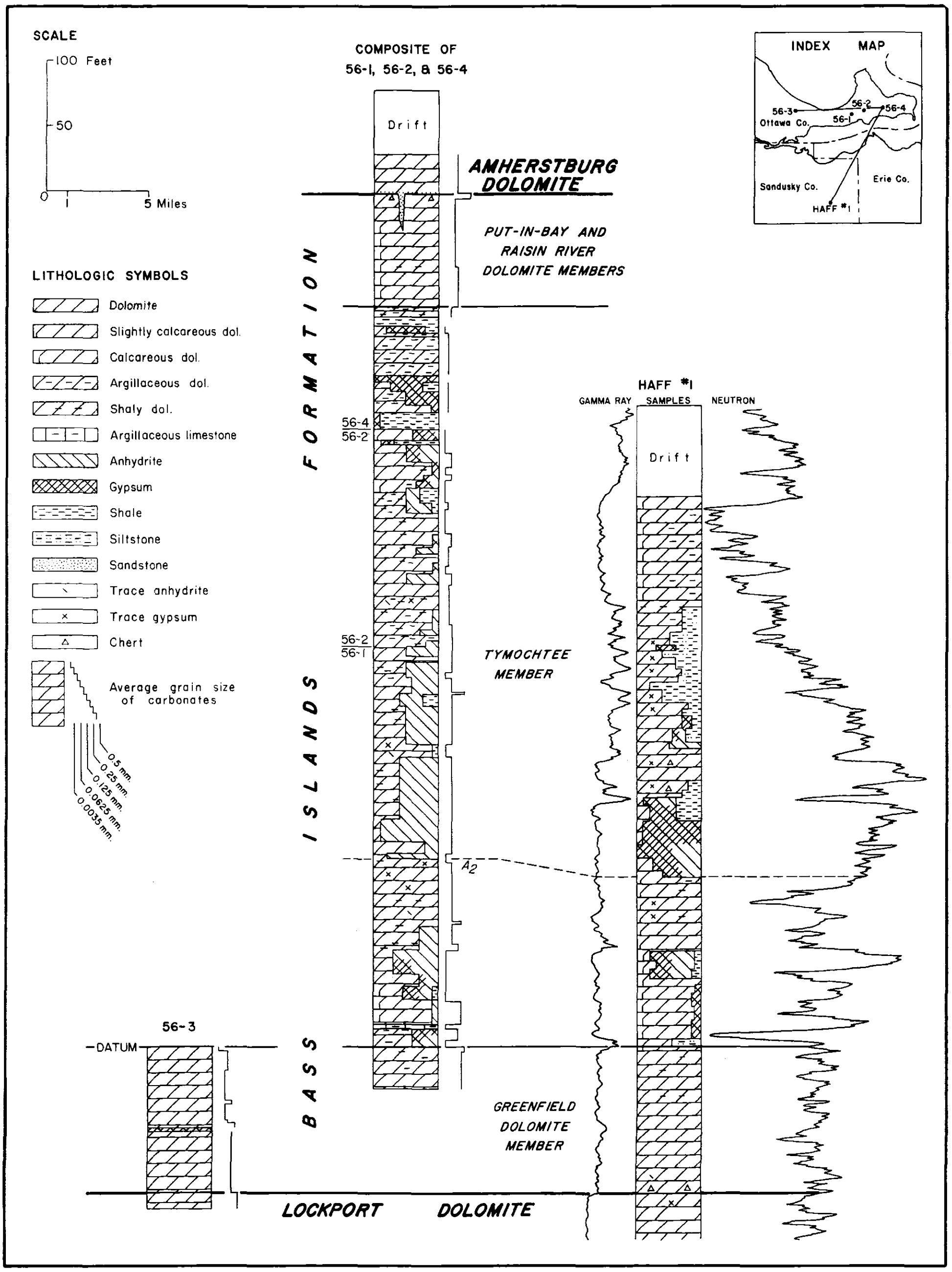
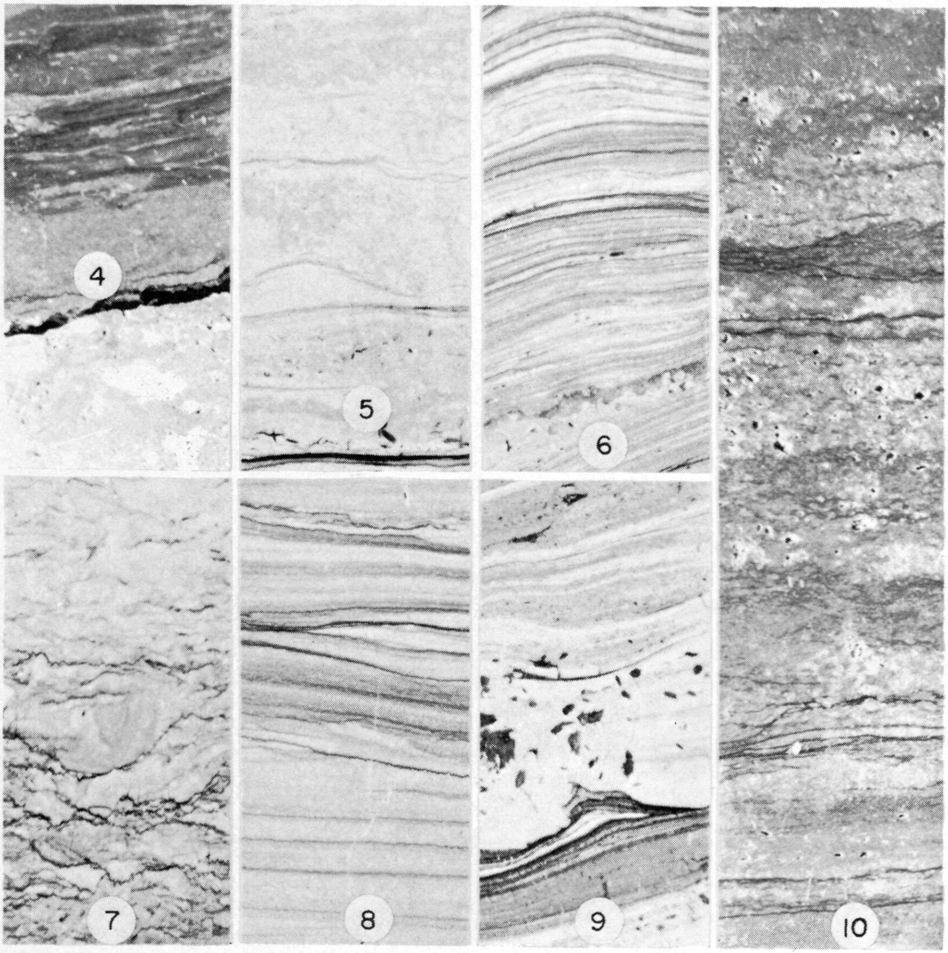


FIGURE 3. Bass Islands Formation in eastern Ottawa and Sandusky counties. Descriptions are from United States Gypsum Company cores 56-1 through 56-4, and samples and gamma ray-neutron log of the East Ohio Gas, Haff #1 well.

Greenfield Dolomite Member

In its type region (Greenfield, Ohio), the Greenfield is characterized by an abundance of carbonaceous laminae attributed to decayed plant material (Napper, 1916), and is differentiated from the overlying Tymochtee by its relatively low content of terrigenous clastic material. In Ottawa County the carbonaceous matter is less abundant, but the lithology—clastic-free dense dolomite—is essentially the same. Outcrops of the lower portion can be found around Lockport



FIGURES 4–10. Polished sections of Greenfield Dolomite, X1. FIGURES 4–9 are from core 56–3, figure 10 from 56–1. FIG. 4. Argillaceous basal Greenfield above light gray Lockport Dolomite. FIG. 5. Rather typical Greenfield lithology, 7 feet above the base. Note the fine, wavy carbonaceous streaks, and gypsum grains near the bottom. FIG. 6. Very finely laminated dolomite, 28 feet above the base. Note the coarse-grained anhydrite near the bottom. FIG. 7. Mottled, very fine-grained, stylolitic dolomite, 52 feet above the base. FIG. 8. Typical finely to very finely laminated dolomite with carbonaceous streaks, microstylolitic in part, 65 feet above the base. FIG. 9. Light-tan to light-brown, very finely laminated microgranular dolomite with disseminated grains of gypsum (dark specks), 111 feet above the base. FIG. 10. Brown fine-grained dolomite, 9½ feet below the top of the Greenfield in core 56–1. Porosity is relatively high, and the dolomite is recrystallized—euhedral rhombs are common. Grain size is smaller and porosity lower near carbonaceous streaks.

outliers in the west-central part of the county (see fig. 1) and at limited areas southward into Sandusky County. Lithologies from core 56–3, in which the Greenfield is 112 feet thick, are shown in figures 4 through 9. Above the unconformable contact with the Lockport (fig. 4) are nine inches of argillaceous to shaly brown dolomite. Above this the dolomite is tan to light gray, microgranular to very fine-grained, generally free of argillaceous matter, and typically finely laminated. Laminae are commonly distorted, suggesting viscous flow prior to final lithification. Gypsum occurs locally as disseminated grains and irregular masses, and a three-foot bed of gypsum occurs about 47 feet above the base of the Greenfield in core 56–3 and in other cores in the same area.

Richard Runvik, of the United States Gypsum Company, traced numerous distinctive beds above the Greenfield in core 56–3 through intervening cores to core 56–1, establishing the correlation shown in figure 3. The Greenfield in core 56–1 is considerably different in aspect, being brown and argillaceous in part, coarser grained, recrystallized, and porous (fig. 10). In the uppermost two and one-half feet, there are vugs and fractures filled with gypsum, and petroliferous zones occur below this.

A minor but significant aspect of the Greenfield is stromatolitic development. This is best seen on the Leiser farm in section 25, Washington Township, northern Sandusky County (fig. 1), where a bedrock high is apparently caused by reef buildup of a stromatolitic zone. Figure 11 shows a mound formed in this zone and flanked by normal thin-bedded dolomite. The thin-bedded dolomite is only a few feet thick and is overlain by brecciated, stromatolitic dolomite (fig. 12). These facies have been described by Summerson (1963), and by Textoris and Carozzi (1966), from a more extensive reef development in the Greenfield near Maumee, on the northwestern flank of the Findlay Arch.

In well cuttings from Ottawa County southward, the Greenfield is generally tan to light-brown pure dolomite, with traces of carbonaceous partings. However, the lower Greenfield in the Valley Oil Company #1 Robinson well (fig. 1) is largely limestone, and limestone was reported at the same level in some samples from north-central Ohio by Ulteig (1964). Eastward from the Findlay Arch, the Greenfield passes into the more argillaceous and shaly dolomites and anhydrites of the A_1 unit (Ulteig, 1964, p. 19).

A pronounced disconformity occurs at the top of the Greenfield in cores from Ottawa County. Considerable relief on this erosion surface is indicated by structural contours based on about 100 control points furnished by the United States Gypsum Company (Sparling, 1965, pl. XXIV). The erosional interval responsible for this surface apparently produced the porous zone in the upper part of the Greenfield in core 56–1. This porous zone can be found at or near the top of the Greenfield well into the Appalachian Basin and is known to drillers as the "Newburg" zone. It can be observed on the neutron curve of the Haff well (fig. 3) just above the top of the Greenfield on the sample log, and shows up consistently on neutron logs of wells to the south and to the southeast of Sandusky County.

The top of the Greenfield, as determined in cores, corresponds almost exactly to the top indicated in the description of a core from the Celotex Corporation quarry, west of Gypsum, in the 1957 Ohio Academy of Science guidebook (Coash, *et al.*, 1957). As shown in figure 2, however, it does not correspond to the top of the A_2, as does the top of the Greenfield of Landes and Ulteig. Instead, it appears to correspond to the unconformity between the A_1 and A_2 of Evans. The A_2 unit, described by Evans as consisting of a lower evaporite portion and an upper dolomite section, corresponds to the lower part of the Tymochtee as indicated in figure 3. Because this unit includes shale and abundant argillaceous dolomite and anhydrite, it cannot logically be identified with the type Greenfield. Furthermore, the writer feels that the type section of the Tymochtee is probably the lateral equivalent of part of the A_2 (Sparling, 1965, p. 94; plate XXII).

FIGURE 11. Reef buildup of stromatolitic facies in the Greenfield Dolomite on the Leiser farm, section 25, Washington Township, Sandusky County. Note the high angle of dip of flanking beds and the pattern formed by small mounds in the foreground.

FIGURE 12. Normal, bedded Greenfield overlain by brecciated-stromatolitic facies on the Leiser farm.

Tymochtee Member

Carman (1927) described the Tymochtee as being the most shaly member of the Bass Islands Formation, and shaliness has come to be the basic criterion for its recognition and differentiation. In Ottawa County, it can be distinguished from the other members on this basis, as well as by its content of anhydrite and gypsum and by its wider variety of dolomite lithologies. The distribution and nature of surface exposures of the Tymochtee were described by Carman and by Miller (1955), who identified it as far south as Adams County, Ohio.

Only the upper part of the Tymochtee is found in surface exposures in Ottawa County. The thickest section occurs on West Sister Island, where Gilbert (1873) described 90 feet of strata and assigned the gypsum-bearing lower 58 feet to the "Onondaga Salt group." The Celotex Corporation quarry near Gypsum exposes about 30 feet of section, the top of which is approximately 90 feet stratigraphically below the top of the Tymochtee. Along the western shores of South Bass Island and the Catawba Island peninsula, Tymochtee outcrops are limited to approximately the upper 15 feet of the unit.

Study of Tymochtee lithologies was based largely on examination of cores 56–1, 56–2, and 56–4. Only the first of these penetrated the entire Tymochtee, which is 559 feet thick at this locality. The upper part of the section in this core shows evidence of extensive conversion of bedded anhydrite to gypsum, as well as some solution and collapse brecciation. The other cores are downdip and are less altered, and were more useful in studying the upper Tymochtee strata.

Several lithologic varieties from the Tymochtee are shown in figures 13 through 30. Dolomite identical to that of the Greenfield is found at various levels, especially near the top of the Tymochtee. Other lithologies include argillaceous dolomite, silty fine-grained dolomite, gypsum, anhydrite, mudstone, shale, breccia, and phenoclastic intraformational conglomerate.

The most common type of rock is sublithographic to microgranular dolomite, but there is no single variety that could be called typical. Generally tan to gray, dolomite occurs in beds ranging from fractions of an inch to several feet in thickness. Most distinct dolomite units are interbedded with anhydrite or gypsum. The thickest section that is essentially free of anhydrite or gypsum interbeds is that which forms the upper part of the A_2 unit. This dolomite unit, about 50 feet thick and relatively resistant to weathering and erosion, forms a buried cuesta trending north-northwesterly through the central part of Ottawa County. This cuesta rises to within 12 feet of the present surface and is reflected by a bulge in the Lake Erie shoreline, in the north-central part of the county.

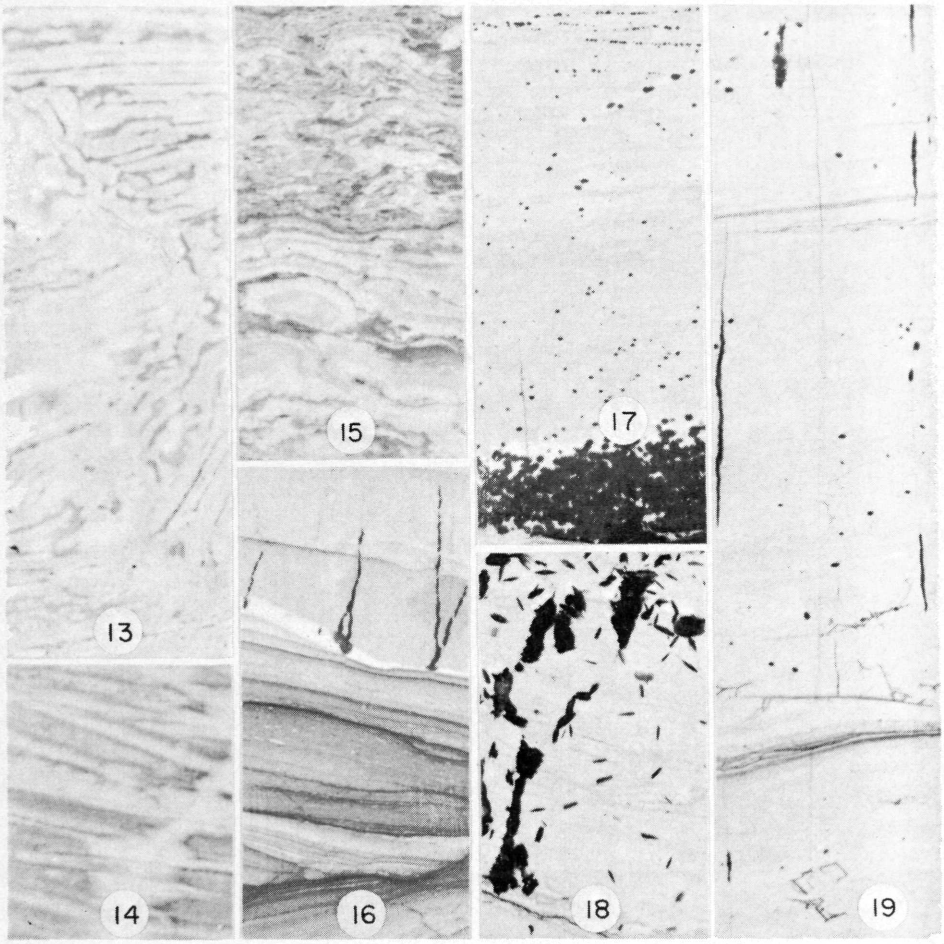
Anhydrite interbeds, ranging from fractions of an inch to several feet in thickness, are generally massive, dense, dark blue in color, slightly translucent, and lacking in primary sedimentary structures. Anhydrite also occurs as irregular replacement masses within beds of dolomite. Some anhydrite is lighter and softer than normal, indicating partial hydration.

Gypsum occurs in two forms. Dark brown gypsum is found as small, clustered to disseminated porphyroblasts, and as fracture fillings, in dolomite. The porphyroblasts range in shape from round to elongate and pointed, and they interrupt, but do not distort, dolomite laminae. The fracture fillings are thin, except where they have been widened by replacement of dolomite. Gypsum also occurs as white-to-gray nodules, irregular replacement masses, and thick beds.

Dark-gray shale generally occurs only as partings and as very thin beds. Thicker argillaceous beds are usually admixtures of clay with dolomite and anhydrite. As pointed out by Ulteig (1964, p. 22), such admixtures are very difficult to classify on the basis of visual examination.

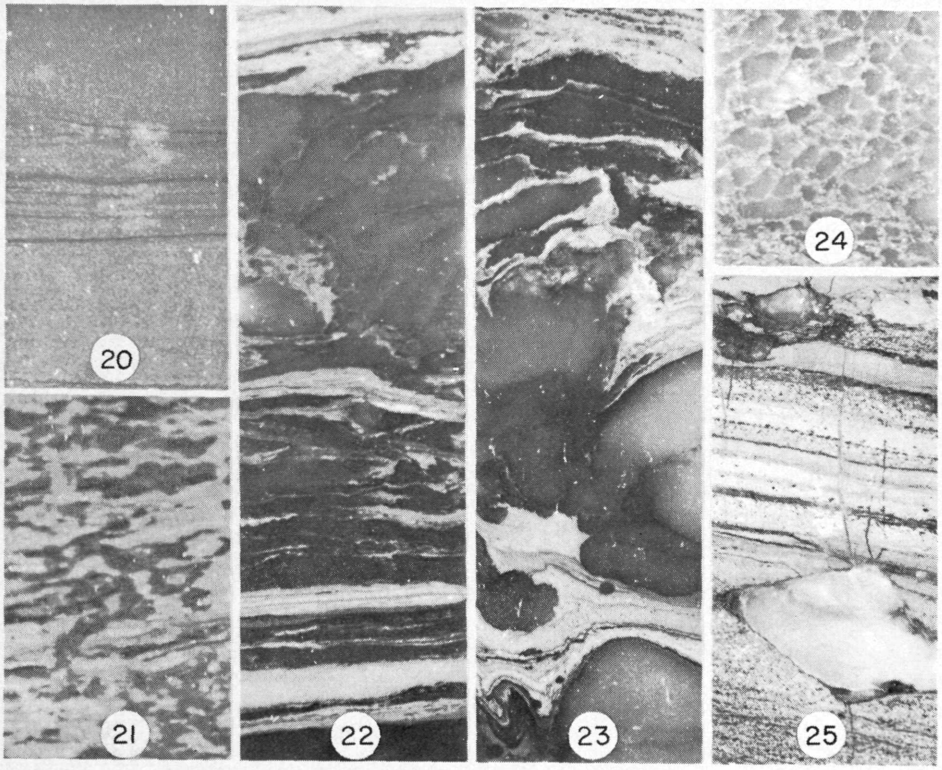
A minor constituent of the upper part of the Tymochtee is coarsely crystalline celestite. Ham (1962, p. 145–146) has shown that strontium can be released from solid solution in anhydrite during hydration to gypsum, which seems to be the most likely source for the celestite found throughout Ottawa County. It occurs as cavity fillings, not only in the Tymochtee, but also in the Lockport and Put-in-Bay dolomites. The most spectacular occurrence is at Crystal Cave, South Bass Island, which is essentially a giant geode in the Put-in-Bay Dolomite, lined with huge (12-inch) crystals of celestite.

Near the village of Gypsum and the site of core 56–1, gypsum is presently being quarried and mined from several thick seams within the upper 120 feet of Tymochtee strata. To the north, however, the mining seams disappear, and the



FIGURES 13–19. Polished sections of Tymochtee lithologies from core 56–1, X1. FIG. 13. Oddly mottled gray sublithographic dolomite, one and a half feet above the base of the Tymochtee. FIG. 14. Greenish gray argillaceous sublithographic limestone, 9½ feet above the base. FIG. 15. Tan to brown dolomite containing masses of white secondary gypsum and light-blue anhydrite, 49 feet above the base. FIG. 16. Tan to brown dolomite with carbonaceous interlaminations, 142 feet above the base. Note the disruption of laminae, apparently from viscous flow. Dark streaks cutting across laminae are gypsum. FIG. 17. Faintly laminated tan dolomite containing disseminated to clustered grains of dark-brown gypsum, 311 feet below the top. FIG. 18. Faintly laminated tan dolomite containing disseminated to clustered coarse euhedral grains of dark-brown gypsum, 202 feet below the top. FIG. 19. Faintly to sharply laminated tan dolomite with dark-brown gypsum occurring as fillings and replacements along vertical fractures, 192 feet below the top.

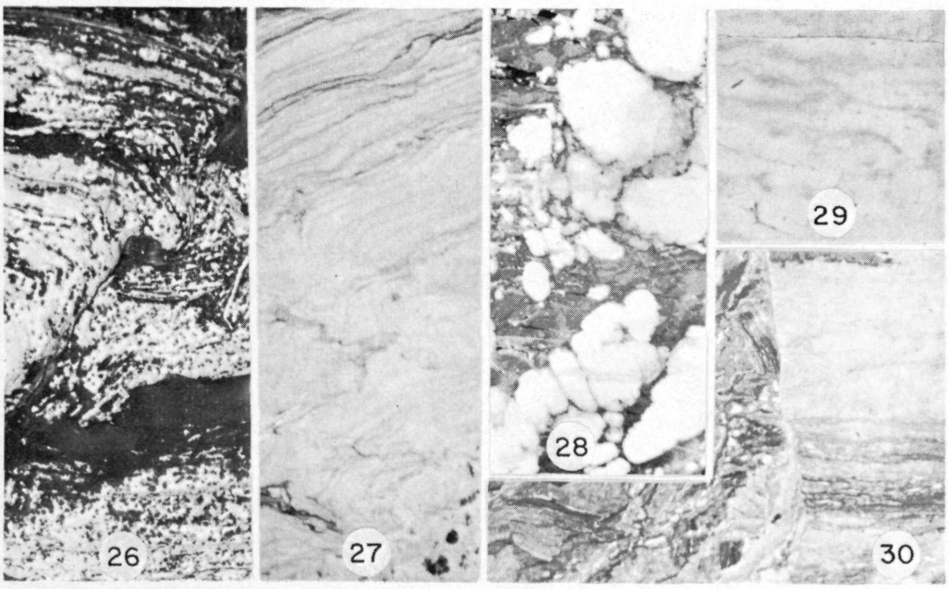
entire Tymochtee thins considerably. Samples from the Clarence C. Hilliard #3 Wiechel well, on the west side of Catawba Island peninsula (fig. 1), indicate a scarcity of gypsum or anhydrite above the A_2 unit, and the total Tymochtee section is more than 100 feet thinner than in the composite section shown in Figure 3. The thinning is of the same order of magnitude as the composite thickness of the missing gypsum beds, and it is evident that gypsum has been removed by ground-



FIGURES 20–25. Polished sections of Tymochtee lithologies, X1. FIG. 20. Silty, argillaceous fine-grained dolomite, 12 feet above the base of the Tymochtee in core 56–1. FIG. 21. Mottled dolomitic, anhydritic mudstone, 356 feet below the top in core 56–2. FIG. 22. Dark-blue anhydrite with interlaminations of tan dolomite, 358 feet below the top in core 56–2. FIG. 23. Distorted beds of partially hydrated blue anhydrite with distorted and partially replaced interbeds of tan dolomite, 187 feet below the top in core 56–2. FIG. 24. Gypsum masses, replacing dolomite (light network), 170 feet below the top in core 56–1. FIG. 25. Finely laminated tan dolomite containing disseminated fine grains of dark-brown gypsum, in part replaced by secondary white-to-gray gypsum, 79 feet below the top in core 56–4.

water solution. The area in question lies along the western margin of a dissected cuesta, formed by the Put-in-Bay and Raisin River dolomites, that was described by Carman (1946). Buried valleys exist to the west of this cuesta, and ground water percolating through the Tymochtee toward these valleys apparently dissolved away most of the gypsum above the A_2, leaving only the dolomites and shales. The massive dolomites above the Tymochtee were let down, without breaking up to any great extent, along the western margin of the cuesta.

With the exception of the area around Gypsum, this condition occurs all along the western part of the cuesta, which extends through the Bass Islands. The easterly regional dip of the Put-in-Bay has been reduced, and locally even reversed, as a result. Verber and Stansbery (1953) pointed out that collapse from removal of underlying gypsum by solution is the most likely cause of various caves found in the Put-in-Bay Dolomite on South Bass Island. Green and Rattlesnake islands, formed of Put-in-Bay Dolomite, represent remnants of a westward shift of the cuesta's edge that could have resulted from removal of gypsum from the entire Tymochtee in this region. The sample log of the Haff well (fig. 3) indicates that there has also been considerable solution of gypsum to the south of Sandusky Bay.



FIGURES 26–30. Polished sections of Tymochtee lithologies, X1. FIGURES 26–29 are from core 56–1, figure 30 from outcrop. FIG. 26. Distorted finely laminated tan dolomite with disseminated grains of dark-brown gypsum and dark bluish-gray anhydrite interbeds, 339 feet below the top of the Tymochtee. FIG. 27. Very finely laminated tan dolomite showing varying degrees of disruption, apparently from viscous flow, 82 feet below the top. FIG. 28. Masses of white secondary gypsum replacing dolomitic mudstone, 80 feet below the top. FIG. 29. Silty, argillaceous mottled green dolomite, 22 feet below the top. FIG. 30. Brecciated dolomite and normal, bedded dolomite at the edge of an apparent filled sink in the uppermost Tymochtee along the northwest shore of Catawba Island.

Greenfield and Tymochtee Sedimentation and Diagenesis

The Greenfield and Tymochtee of Ottawa County were deposited in the shallow margin of an extensive evaporite basin, created as the result of restriction of circulation by buildups of reefs and shallow banks in the basin-rim areas during Niagaran time (Alling and Briggs, 1961). Penesaline conditions prevailed, and the Greenfield and those strata in the Tymochtee having Greenfield-type lithology apparently represent the lowest salinity range. Salinity was low enough, at least part of the time, to permit the existence of *Leperditia* and rather abundant plant life. However, salinity higher than that in normal marine conditions is indicated by the meager fossil assemblage and possibly by the fact that carbonaceous matter was preserved.

The unconformity at the top of the Lockport and the argillaceous basal Greenfield in core 56–3 indicate that normal marine sedimentation and the onset of hypersaline conditions were separated by a period of emergence. However, in the lowest part of the quarry at Maumee, Niagaran corals are surrounded and overlain by typical Greenfield dolomite with no evidence of any break in sedimentation. In addition, many workers have suggested that late Niagaran marine sedimentation in the shallow margins of the basins may have been contemporaneous with evaporite sedimentation in deeper waters (Liberty and Bolton, 1956, p. 168; Alling and Briggs, 1961, p. 539; Pinsak and Shaver, 1964, p. 55).

The presence of stromatolitic facies in the Greenfield indicates very shallow conditions, as stromatolites are believed to form mainly in intertidal zones. The clasts in breccias associated with this facies may well have been products of subaerial desiccation during periods of emergence. The stromatolitic development exposed on the Leiser farm forms a domal structure which probably began as a topographic high in the shallow sea. The underlying Lockport Dolomite is characterized by local highs (such as the outliers shown in figure 1), and Greenfield stromatolitic mounds may have developed over these Lockport highs through differential compaction of surrounding carbonate muds.

Alling and Briggs (1961, p. 539) suggested that the algal-stromatolite mound near Maumee owed its existence to proximity to an inlet into the Michigan Basin from the Kokomo Sea to the southwest, which assured a supply of "fresh ocean water." This may account for the large size of the Maumee mound, but the paleogeography of Alling and Briggs (1961, fig. 12) indicates that the mound on the Leiser farm does not lie near such an inlet and was separated from the Kokomo Sea by a broad Niagaran reef bank. It would thus appear that conditions of similar salinity may have existed at many points along the Niagaran barrier banks. This supposition is consistent with the "leaky-reef" pattern of influx all around the basin margins called for in a study by Briggs and Pollack (1967), as opposed to the restricted influx suggested by Alling and Briggs (1961).

Carbonate streaks and slightly greater average grain size distinguish the typical Greenfield lithology from most of the dolomite in the Tymochtee. The presence of limestone in some areas indicates that the original sediment consisted mainly of calcium carbonate. Scarcity of fossils suggests that the original sediment resulted mainly from carbonate precipitation, possibly under chemical conditions controlled by plant activity. Dolomitization of the Greenfield, and of similar lithologies in the Tymochtee, very likely resulted from seepage refluxion of magnesium-rich brines, as described by Adams and Rhodes (1960). The presence of limestone in limited areas may reflect local permeability barriers.

The porous dolomite shown in Figure 10 seems to represent a secondary development that resulted from solution and recrystallization during the erosional interval that produced the disconformity at the top of the Greenfield. This facies is not found in core 56–3, and it may be that extensive solution and recrystallization occurred only where there was a high initial gypsum content.

Dolomites other than those of the typical Greenfield variety appear to be true evaporite carbonates. Whether they were precipitated as calcitic or dolomitic carbonate is not clear, but Siegel (1961) has shown that direct precipitation of dolomitic carbonate is possible in the presence of sulfate gel under normal conditions of temperature and pressure. The disseminated gypsum in many dolomites (see figs. 9, 17–19) is ample evidence that sulfate ions were an important constituent of the original sediments. The nature of the original sediments is suggested by Siegel's discussion of the reactions involved and by the sedimentary features shown by polished sections of dolomite. In Siegel's experimental work, intermediate products interpreted as being "calcium sulfate gel and hydrated magnesium ion gel" were formed. The final products were dolomitic carbonate, calcium sulfate, calcium carbonate, and hydromagnesite. Some of the polished sections of Tymochtee dolomite indicate that the sediments were at some stage subjected to viscous flow (figs. 13, 15, 16, 26, 27), and the viscous nature may have been caused by the presence of gels similar to Siegel's intermediate products. Lithification may have begun with formation of crystalline dolomitic carbonate and expulsion of water, and ended with partial replacement of dolomite by concentrated hydrous calcium sulfate. This paragenetic relationship is suggested by the disseminated grains and replacement masses of gypsum seen in several of the polished sections. Figures 16 and 19 show a fairly common condition, suggesting that replacement has been concentrated along vertical fractures which might have been produced by volume reduction during transformation from the gelatinous to the crystalline state.

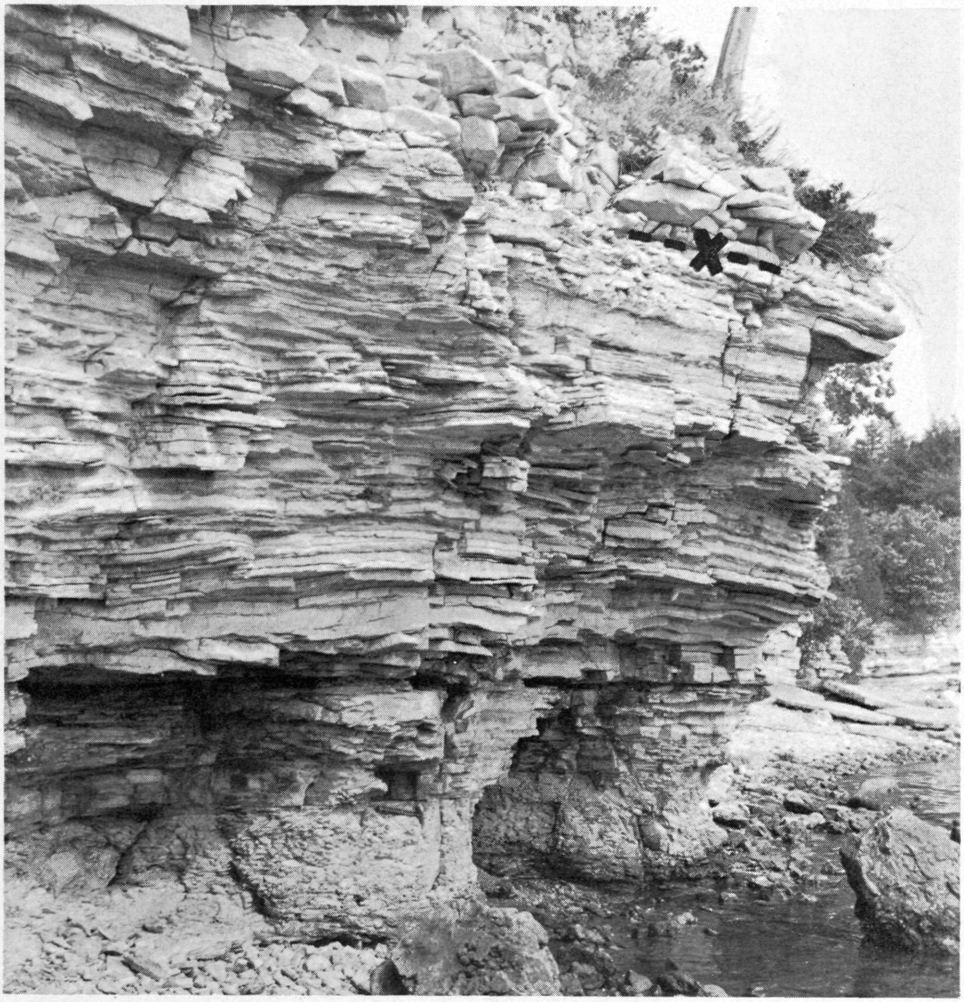


FIGURE 31. Uppermost Tymochtee and lowermost Put-in-Bay on South Bass Island near the northwestern limit of the state park. The relatively massive mudstone at the bottom was considered uppermost Tymochtee by Carman and Mohr. The Tymochtee/Put-in-Bay contact of the writer is marked by an X.

It thus seems possible that many Tymochtee beds, especially those that are sublithographic and gypsiferous, originated as dolomitic precipitates. Some of the other carbonates, however, may represent original calcium carbonate precipitates that were partially to completely dolomitized. A single bed of argillaceous limestone (fig. 14) shows that evaporite calcium carbonate was indeed deposited; many of the microgranular to fine-grained dolomites probably represent dolomitized and recrystallized calcium carbonates. Original calcite or aragonite precipitates could have been dolomitized by seepage refluxion wherever permeability was adequate.

The thin anhydrite interbeds appear to represent rhythmic, possibly annual,

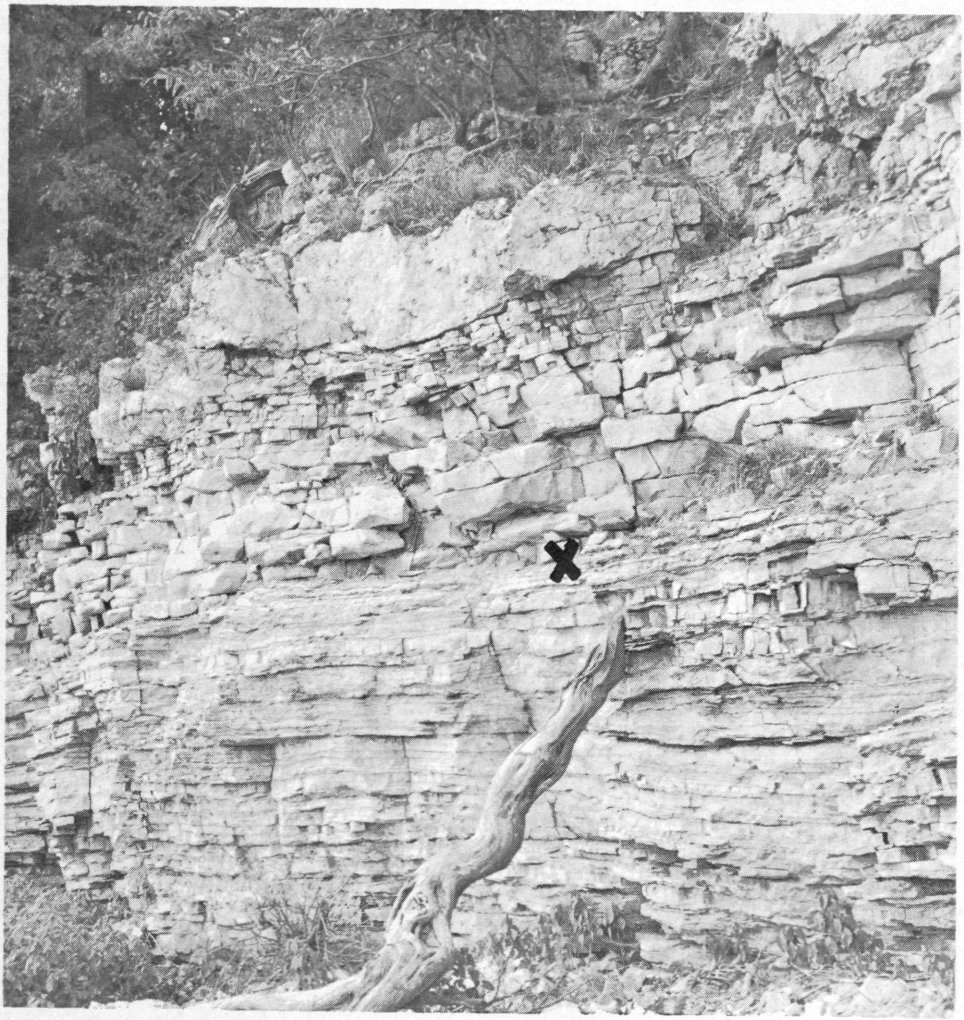


FIGURE 32. Tymochtee/Put-in-Bay contact (X) just northwest of the site shown in figure 31. Note the clearer lamination and thinner bedding of the Tymochtee. A disconformity separates it from the lowest bedded unit of the Put-in-Bay, which is overlain by a massive brecciated unit.

increases in salinity. The thicker units indicate prolonged periods of elevated salinities. Murray (1964) has pointed out that such anhydrites probably do not represent primary precipitates, and their lack of primary sedimentary structures supports this view.

The dark-brown granular gypsum found disseminated in dolomite shows no evidence of having been altered in any way, and all of the primary sulfate sediment may have had this form. Enclosure in dolomite apparently prevented dehydration of most of these disseminated grains. However, some clusters of primary grains and all of the original bedded gypsum lost the water of hydration and were thus converted to anhydrite subsequent to burial. Extensive replacement of dolomite interbeds accompanied this conversion. The massive gray-to-white gypsum occurring as beds, cavity fillings, and irregular replacement masses is clearly a product of secondary hydration of anhydrite by ground water.

The thin dark shales in the Tymochtee appear to represent deposition in quiet water during periods when no precipitates were forming. The dolomitic and anhydritic mudstones, as well as the very argillaceous dolomites, indicate that evaporite and clay sedimentation frequently proceeded simultaneously and at rather constant rates.

Uppermost Tymochtee and the Upper Tymochtee Contact

The top of the Tymochtee in Ottawa County was placed by Carman (1927,

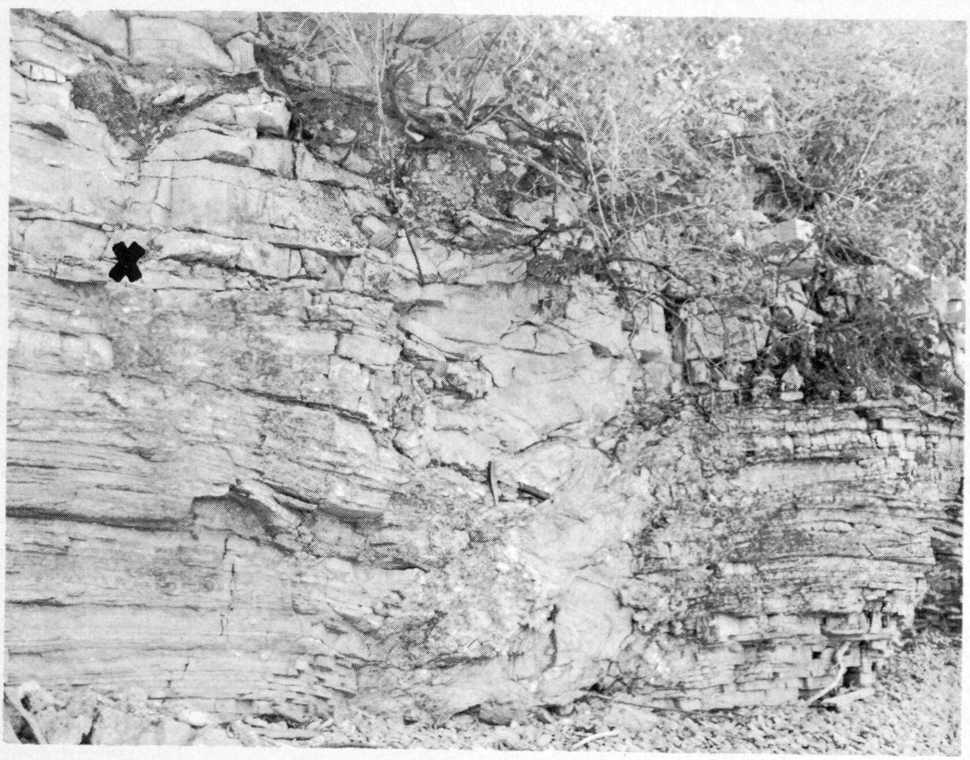


FIGURE 33. Breccia in what appears to be a filled sink at the top of the Tymochtee, near the southern tip of South Bass Island. The X marks the contact with the lowest bedded unit of the Put-in-Bay, which extends essentially uninterrupted across the top of the bececia. Figure 30 shows breccia from a similar feature on Catawba Island.

p. 488) and Mohr (1931, p. 26, 29) at the top of a bluish-gray dolomitic mudstone, which can be found at a few places along the shores of Catawba Island and South Bass Island and is shown in figure 31. However, at the site of figure 31, this mudstone is conformably overlain by about 10 feet of nonfossiliferous thin-bedded dolomite identical in lithology to a dolomite unit 4 feet in thickness that is found 2 feet below the top of the mudstone; identical dolomite also occurs at various levels in the Tymochtee in cores examined by the writer. In addition, the dolomite in question bears only superficial resemblance to any lithologic varieties found in the overlying Put-in-Bay and Raisin River dolomites. Accordingly, this thin-bedded dolomite above the mudstone, which totals about ten feet on South Bass Island and seven feet in core 56–4, is included in the Tymochtee.

FIGURE 34. Large brecciated channel cut into the lowest Put-in-Bay unit and the upper Tymochtee along the northwest shore of Catawba Island. The channel breccia appears to be in continuity with the second, brecciated unit of the Put-in-Bay. The Tymochtee/Put-in-Bay contact is marked by an X.

The top of the Tymochtee as thus defined is normally a disconformable surface, marked by a thin seam of clay and showing a few inches of local relief. Typical examples of the contact with the Put-in-Bay are shown in Figures 31 and 32. The uppermost Tymochtee is thin-bedded, very finely and clearly laminated, and weathers tan. The basal Put-in-Bay is thicker bedded, finely and faintly laminated, and weathers gray. This lowest Put-in-Bay is overlain by a massive brecciated dolomite, which can be seen in Figure 32.

The normal condition in the uppermost Tymochtee is interrupted at various places by two distinct types of breccia. One type is shown in Figure 33. Here clasts are composed of Tymochtee rock types, and the breccia is overlain by normal, bedded Put-in-Bay Dolomite. Figure 30 shows the contact between bedded strata and breccia from a like feature on Catawba Island. These breccias apparently developed prior to Put-in-Bay sedimentation, probably by collapse into sinks formed by solution of underlying gypsum during the interval of erosion which produced the disconformity at the top of the Tymochtee.

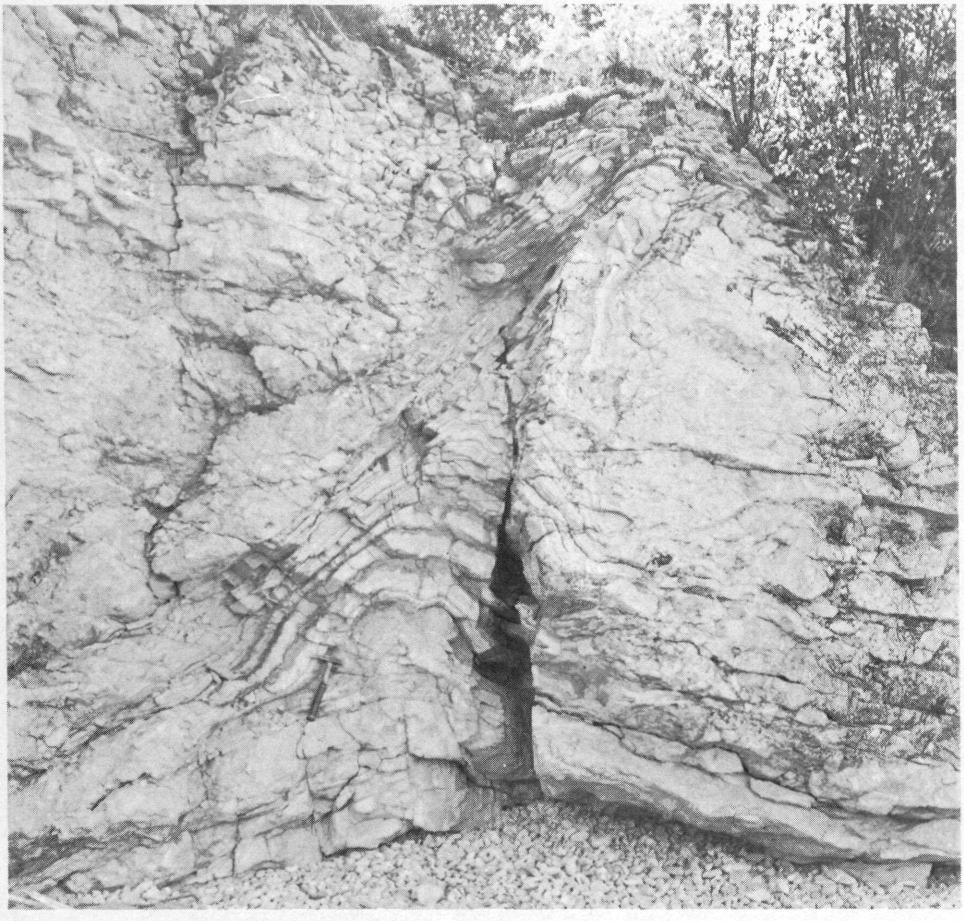


FIGURE 35. Isoclinally folded uppermost Tymochtee strata within Put-in-Bay channel breccia, northwest shore of Catawba Island. The deformation appears to have been caused by breccia flow, prior to final lithification of any of the strata involved.

The second type of breccia is shown in Figure 34. Here the clasts are a mixture of Tymochtee and Put-in-Bay lithologies, indicating that brecciation occurred after initial Put-in-Bay sedimentation. As seen in Figure 34, these breccias appear to occupy channels cut into the upper Tymochtee. The lowest bedded unit in the Put-in-Bay is also truncated by the channel, and the breccia is continuous with that of the second Put-in-Bay unit. These breccias are interpreted as having been debris flows which eroded channels in the Tymochtee, breaking it up and incorporating blocks of it. Most of the channels are seen in cross section, possibly because outcrops trend parallel to the strike of the paleoslope. At one point along the northwestern shore of Catawba Island, however, a cliff cuts obliquely along a channel, and the feature shown in Figure 35 can be observed. Here the debris flow apparently tore the upper part of the Tymochtee loose, pushing it into an asymmetric isoclinal fold. The origin of these debris flows is discussed later in connection with the Put-in-Bay Dolomite.

FIGURE 36. Brecciated interval near the top of the Tymochtee and adjacent to a breccia channel, northwest shore of Catawba Island.

In addition to the breccias discussed above, intraformational conglomerates and breccias occur within definite stratigraphic intervals just below, but not at, the top of the Tymochtee. When seen in outcrops, these are associated with the channel breccias, in some cases being continuous with them and grading laterally away from the channels into normal bedded dolomite within several feet. Figure 36 shows one of these breccias a few feet from a channel, along the shore of Catawba Island. It seems likely that these conglomerates and breccias were formed by disruption of normal bedded sediments owing to drag created by the debris flows in the channels.

Put-in-Bay and Raisin River Dolomites

The "Put-in-Bay dolomites" were first referred to by Sherzer and Grabau (1909, p. 546). Named for exposures on South Bass Island, the unit was stated (Lane, Prosser, Sherzer, and Grabau, 1909, p. 554) to be over 100 feet thick at the type locality, where it was said to be overlain by the Raisin River. No lithologic description was given. An abundance of the pelecypod *Goniophora dubia* Hall was the only definitive characteristic given, and the unit was designated the *Goniophora dubia* zone. The overlying "Raisin River dolomites" were designated the *Whitfieldella prosseri* zone, and lithologic description was limited to mention of several zones of oolite.

The Raisin River was named for exposures along the river of that name in Monroe County, Michigan. The most complete description of it in its type region was made by Grabau and Sherzer in 1910 (p. 35–40), who said that it was about 200 feet thick there, although neither the basal contact nor the supposedly underlying Put-in-Bay were discussed. The Raisin River was described as "dolomitic calcilutites and oolites . . . generally thin-bedded and more or less shattered and broken." Local to general brecciation was noted. It is significant that the diagnostic *Whitfieldella prosseri* zone was found to overlap the zone of *Goniophora dubia* by about 51 feet in Raisin River strata in the Detroit salt shaft (p. 39–40).

The units as originally defined were first worked out in detail in the Bass Islands by Mohr (1931). The Put-in-Bay was found to be 45 to 50 feet thick, including about nine feet which the present writer considers to be Tymochtee. The most complete section was found along the western shore of South Bass Island north of its southern tip. Seven units were recognized, and abbreviated descriptions, after Mohr, are as follows:

7.	Massive, brecciated, dark gray to buff dense dolomite.....	13 feet plus	
6.	Thin-bedded, laminated, porous, buff dolomite...........	9 "	
5.	Dense, massive, brecciated, gray-buff dolomite...........	8 "	1 inch
4.	Dense, thin-bedded, gray argillaceous dolomite...........	5 "	2 inches
3.	Thin-bedded, laminated, shaly, gray to buff dolomite.....	8 "	8 "
2.	Thin-bedded, argillaceous, light brown dolomite..........		5 "
1.	Thin-bedded, laminated, gray-drab dolomite.............		2 "

Units 1, 2, and 3 are considered to be Tymochtee by the present writer, and were found by Mohr to be unfossiliferous. These units can be seen in Figure 31. Unit 4 and the lower part of unit 5 are shown in Figure 32. Units 5, 6, and 7 were described by Mohr as showing lateral variation, with breccias grading into bedded strata and vice versa. Distribution of Put-in-Bay strata in the Bass Islands as determined by Mohr is shown in Figure 1. The diagnostic *Goniophora dubia* was found at various points on the main portion of South Bass Island, though not on the northeastern peninsula nor on the southern tip of Middle Bass Island.

The Raisin River was described by Mohr as consisting of strata that are "on the whole thin-bedded, although locally they are brecciated like the other members of the Bass Island formation." The contact with the underlying Put-in-Bay was not located, but the Raisin River was identified as cropping out near the narrow neck between the southwestern and northeastern parts of South Bass Island and along the eastern shore of the latter part. It was also said to form the bedrock of all of North Bass Island and all of Middle Bass Island except the southernmost part. The index fossil *Whitfieldella prosseri* was found in most of the strata assigned to the Raisin River. No specific criteria were offered by Mohr for differentiating the Raisin River from the Put-in-Bay on a lithologic basis, although it may be presumed that brecciation was considered more characteristic of the latter.

The brecciated condition was also considered an important characteristic of the Put-in-Bay by Carman (1927, p. 490), who differentiated it from the Raisin River on this basis in Ottawa County. To the south, however, Carman (1927, p. 495) found that brecciation was lacking in strata that could be correlated with the Put-in-Bay on a paleontologic basis.

The nature and degree of the brecciation seems to be the only basis for lithologic differentiation in the Bass Islands, the surrounding islands, and the Canadian islands to the north and northwest. Although the brecciated zones in the Put-in-Bay grade laterally into normal, thin-bedded dolomite at various stratigraphic levels, these zones, as a whole, form continuous units. By contrast, breccias in the *Whitfieldella prosseri* zone tend to be discontinuous, clasts are smaller, and displacement of the clasts from their original position is slight. In addition, much of the rock above the Put-in-Bay that appears to be brecciated is really pseudobreccia, lacking clearly defined clasts and probably formed primarily by solution and recrystallization.

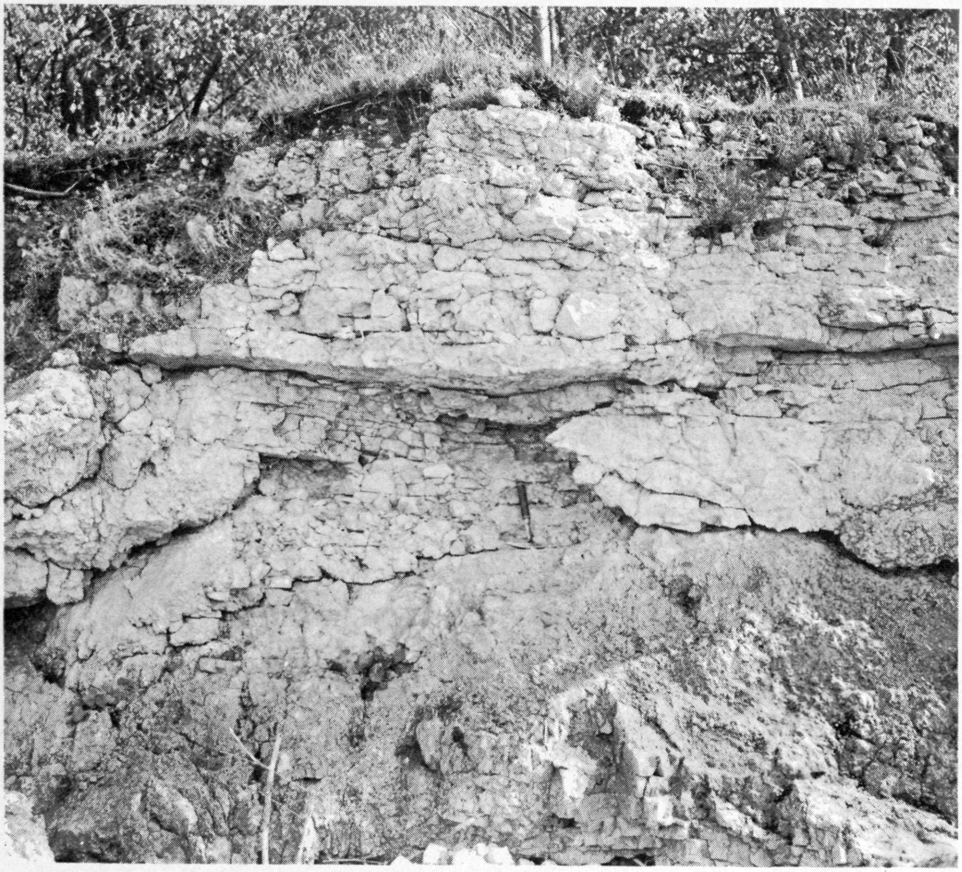


FIGURE 37. Upper strata of the Put-in-Bay Member along the northwest shore of the northeastern arm of South Bass Island. Note the lateral discontinuity of bedded and brecciated phases.

Differentiation of these members in the subsurface is more difficult. In core 56–4, which contained $87\frac{1}{2}$ feet of Silurian strata above the top of the Tymochtee, the lower layers do not show any significant lithologic differences from the upper. Breccias were noted at various levels, but in a core there is obviously no way of telling whether these are continuous, as in the Put-in-Bay, or discontinuous, as in the Raisin River. An oolitic zone, such as is supposed to be characteristic of the Raisin River, was noted, but its top was only 26 feet above the top of the Tymochtee, so that it should be within the Put-in-Bay stratigraphic interval as defined by Mohr.

A core from the quarry on Marblehead Peninsula was studied by Kerr (1950), who found the Put-in-Bay and Raisin River to total 74 feet in thickness. Kerr also expressed difficulty in separating the units on lithologic grounds, but assigned the lower 57½ feet to the Put-in-Bay, stating that it was more argillaceous and

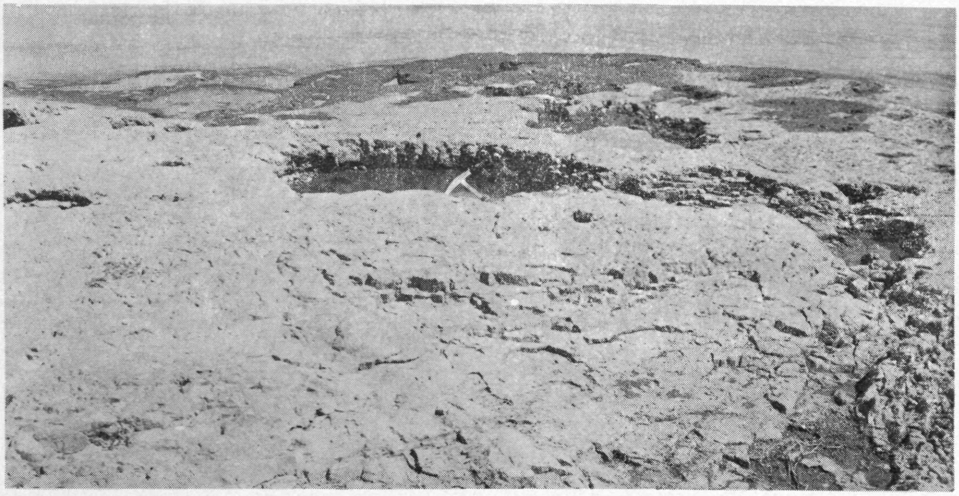


FIGURE 38. Circular brecciated areas among thin-bedded strata in the lower part of the Raisin River, southeast shore of the northeastern peninsula of South Bass Island.

FIGURE 39. Mound of pseudobreccia in the upper part of the Raisin River, north shore of the northeastern peninsula of Middle Bass Island.

calcareous than the Raisin River. However, both Carman (1927, p. 492) and Mohr (1931, p. 43) described the Raisin River as being argillaceous.

It seems apparent that only surface exposures of the Put-in-Bay and Raisin River members lend themselves to lithologic differentiation. Even here, the known Put-in-Bay as defined by Carman is restricted to Catawba Island and the Bass Islands in Ottawa County and to the Holland quarry in Lucas County (Carman, 1927, p. 490–491). In other areas, the only suitable name for strata that are lateral equivalents of these members is Bass Islands Formation.

The appearance of the lower two units of the Put-in-Bay, shown in Figure 32, is more or less typical of the entire member. However, as seen in Figure 37, bedded units and massive brecciated units are not as sharply delineated in the upper part of the member.

FIGURE 40. Mounds, probably of algal origin, in the upper part of the middle unit on Hen Island.

Typical discontinuous breccias and pseudobreccias in the Raisin River are shown in Figures 38 and 39. Figure 38 shows brecciated zones in the lower part of the Raisin River on South Bass Island. Here they are circular to oblong in plan view, several feet in diameter, and tend to be more or less regularly spaced. The centers appear to be well brecciated and many have been so weathered as to leave shallow depressions. The intervening areas, roughly equal in area to the space occupied by the brecciated zones, consist of normal, thin-bedded dolomite. Near the top of the member, as exposed along the northeast shore of Middle Bass Island, there are masses composed mainly of pseudobreccia, with centers spaced about the same distance apart as those shown in Figure 38, but which are much smaller, occupying a small percentage of the area (fig. 39). True brecciation here is slight, and the resulting rock is more resistant to erosion than the surrounding thin-bedded dolomite and forms small mounds.

Areas of Raisin River outcrops in the Bass Islands are characterized by low relief, and exposures along cliffs are usually limited to a few feet of vertical section. Better exposures are found in the Canadian islands to the north and northwest, shown in Figure 1. These islands were studied by Williams (1919, p. 91–92), who found specimens of *Whitfieldella prosseri* at several points in strata presumably all within the Raisin River interval. Strike of the beds trends roughly parallel to the trend of the islands, and dips are generally to the southwest.

On Hen Island there are three distinct units separated by disconformities.

The lowest, $7\frac{1}{2}$ feet thick, consists of finely laminated to massive and brecciated dolomite. The middle unit is $5\frac{1}{2}$ feet of laminated, thin-bedded dolomite in which brecciation is absent. Cross-bedding is fairly common in this unit, and small mounds, probably of algal origin, are found at the top (fig. 40). The upper unit is more than 10 feet in thickness and consists of finely laminated, largely oolitic dolomite interrupted by brecciated zones that are approximately equivalent, in size and areal extent, to those shown in Figure 38. When observed along cliffs, the boundaries of the breccias are seen to be quite abrupt and roughly vertical (fig. 41).

The strata on North Harbor Island resemble the upper unit on Hen Island.

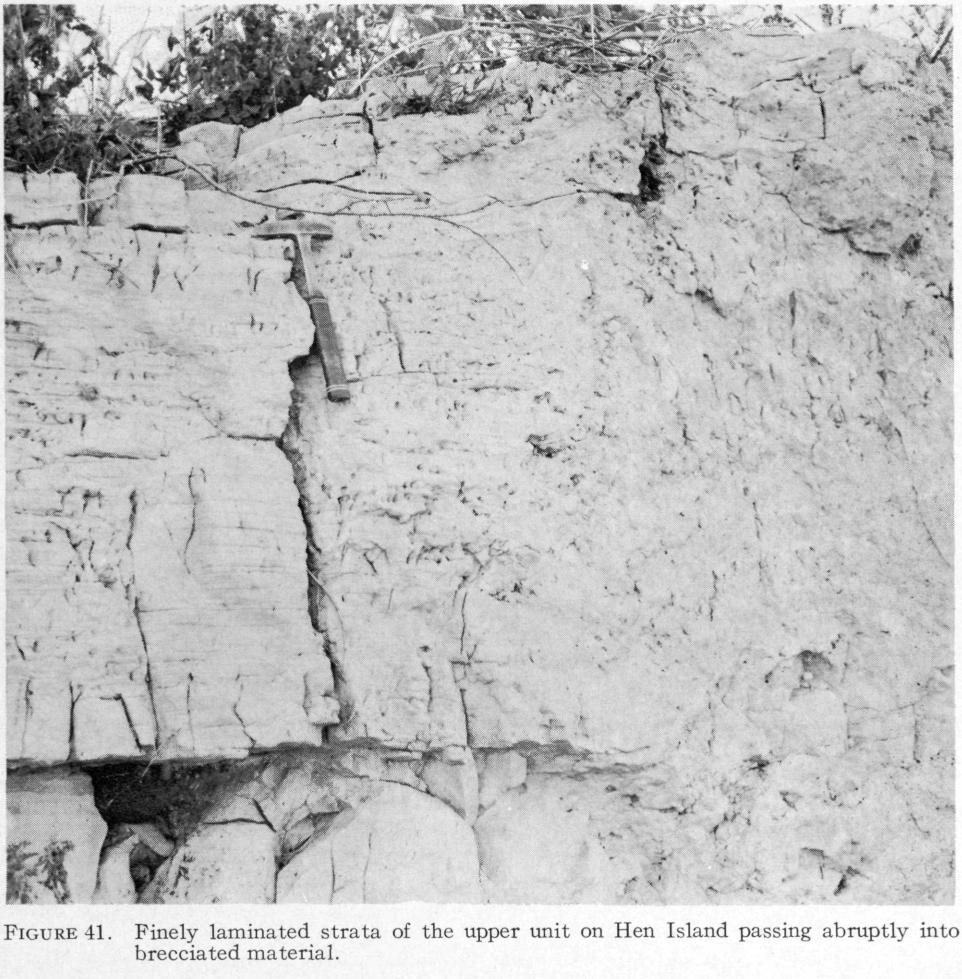


FIGURE 41. Finely laminated strata of the upper unit on Hen Island passing abruptly into brecciated material.

Those on East Sister Island appear to be stratigraphically higher and consist of relatively massive dolomite that is dominantly oolitic. On Middle Sister Island the strata are mostly thin-bedded, and brecciation is very limited. The dolomite is fairly silty, and there is at least one thin bed of siltstone (fig. 42).

The Put-in-Bay and Raisin River dolomites are generally light gray to tan and light brown, calcareous in part, microgranular to very fine-grained, and finely laminated to homogeneous. Typical varieties are shown in Figures 43 through 57. Fossils are generally rare and small, but become abundant along thin intervals at various stratigraphic levels. Average content of argillaceous material is higher than in the Greenfield, but lower than in the Tymochtee. Carbonaceous streaks occur at a few levels.

Post-Tymochtee Bass Islands Sedimentation

The Silurian strata above the Tymochtee in the Findlay Arch region were deposited on a broad shelf, which became emergent following Tymochtee sedimentation and was then inundated by a new transgressive phase. This shelf region was situated between open seas to the south and east and the restricted, in part penesaline, sea occupying the Michigan Basin.

Sedimentation consisted mainly of carbonate deposition in fairly clear, hypersaline water. The thin zones containing small pelecypods and brachiopods prob-

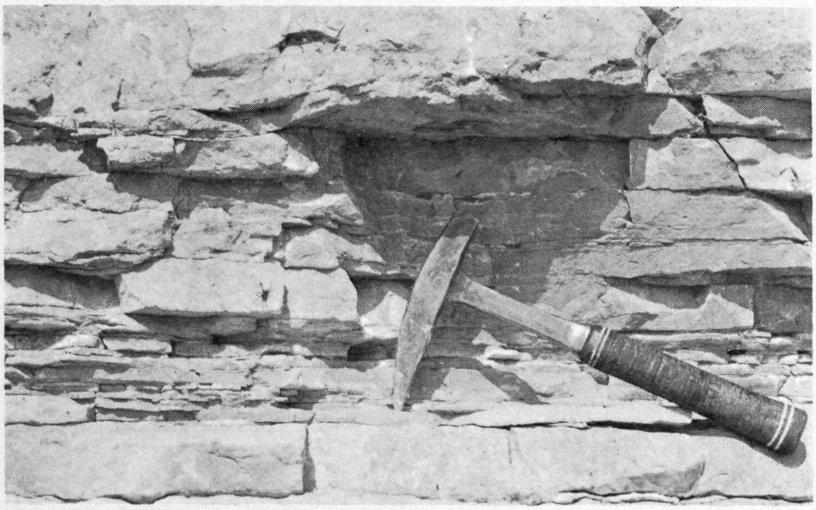
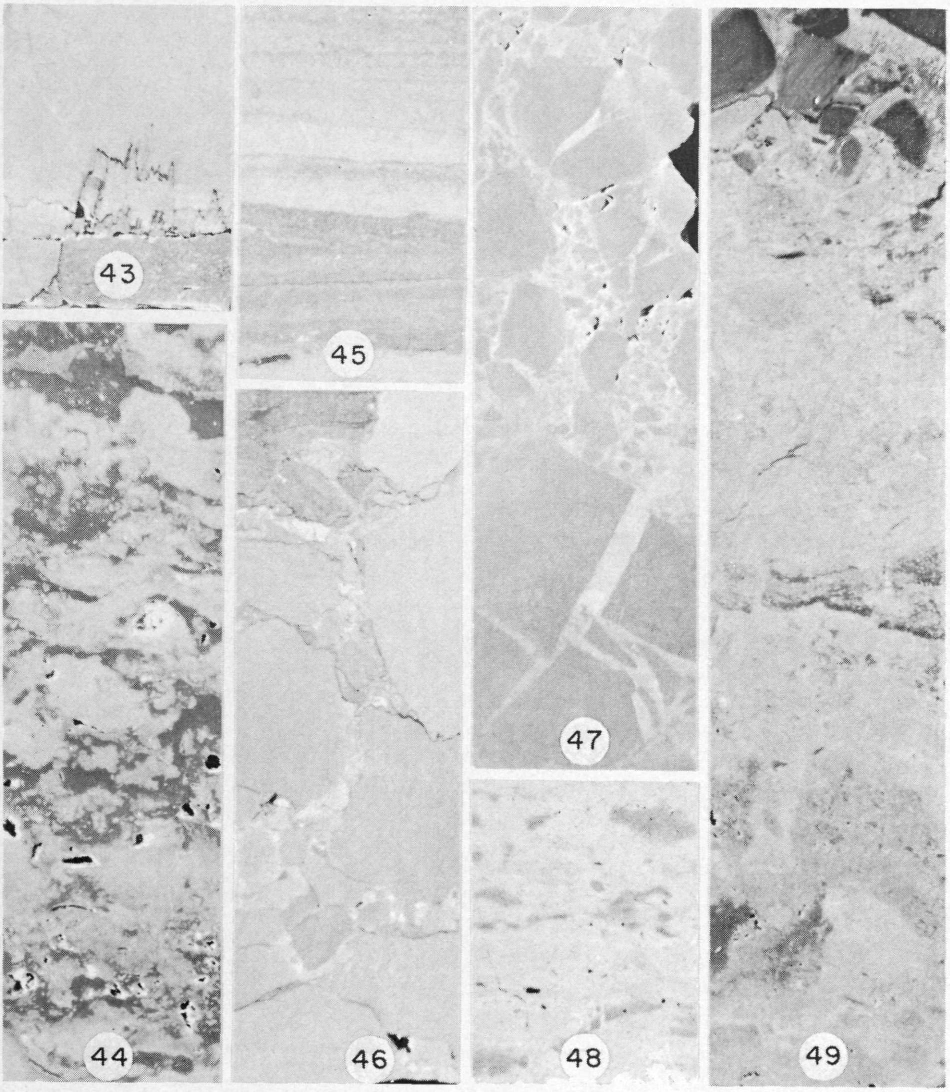


FIGURE 42. Siltstone and silty dolomite on Middle Sister Island.

ably indicate brief, intermittent periods when salinity was close to normal. The *Goniophora dubia* zone contains a low number of species compared to that of the *Whitfieldella prosseri* zone, indicating that salinity probably decreased as time—and transgression—went on. Shallow conditions and intermittent emergence are indicated by cross-bedding, mudcracks, oolites, and breccias. Terrigenous clastic admixtures were restricted to clays during the initial phase, but silt and sand are found in the higher strata. Williams (1919, fig. 5 and p. 91) reported sand in the uppermost Bass Islands Formation in southwestern Ontario.

The original sediments were probably mostly calcium carbonate, composed of hard parts of shells and precipitates, similar in origin to the Greenfield sediments but produced at lower prevailing salinities. As with the Greenfield, plant activity may have played an important role by controlling the chemical environment. Lamination in the bedded dolomite may reflect cyclic changes in salinity and carbonate production.

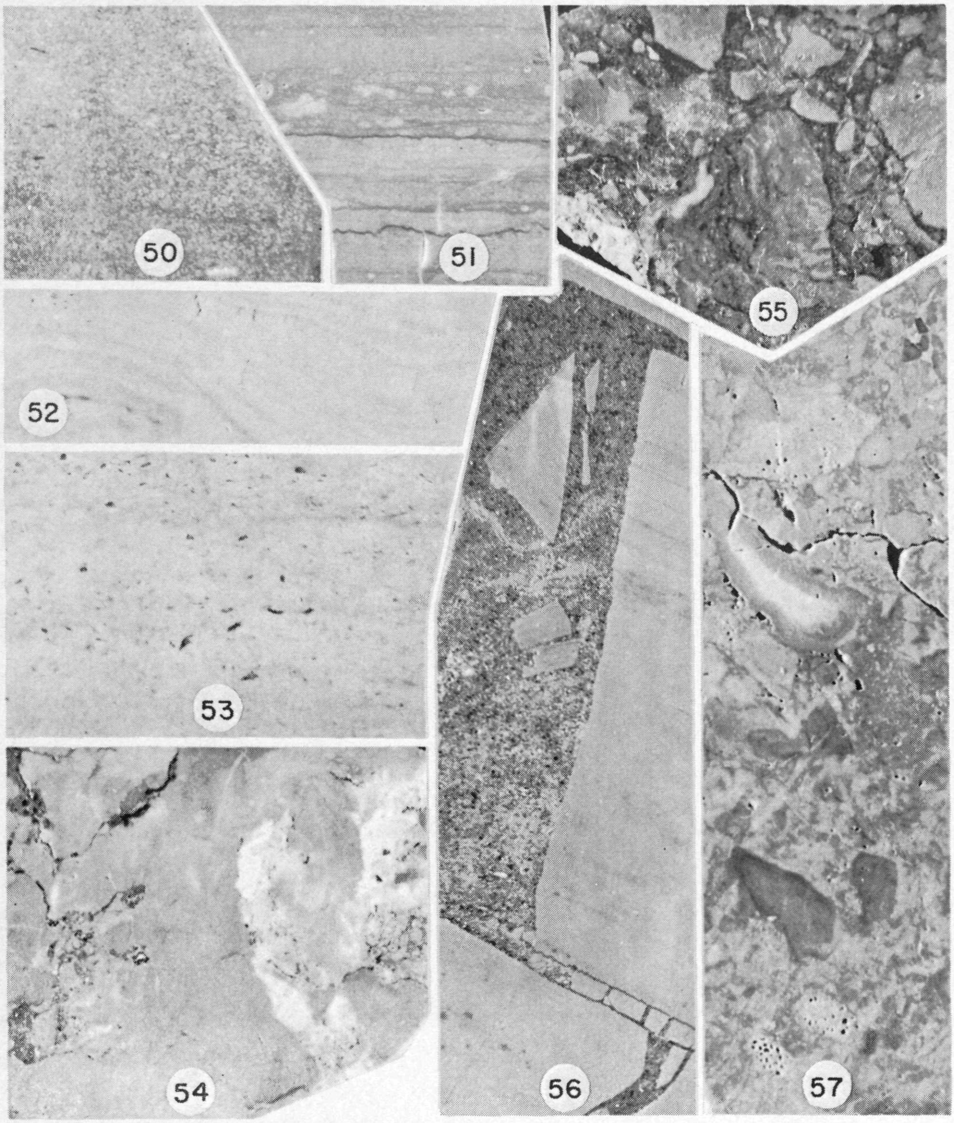
The most striking feature of the strata is the brecciation. The more or less continuous breccias of the Put-in-Bay were discussed by Carman (1927, p. 491), who noted a direct relationship between the size of clasts and the thickness of



FIGURES 43–49. Polished sections of Put-in-Bay and Raisin River dolomites, X1. FIG. 43. Tan basal Put-in-Bay Dolomite from the west shore of Catawba Island. FIG. 44. Mottled tan to light-brown dolomite, 9½ feet above the top of the Tymochtee in core 56–1. FIG. 45. Laminated tan dolomite 12 feet above the top of the Tymochtee in core 56–1. FIG. 46. Tan brecciated dolomite 14½ feet above the top of the Tymochtee in core 56–4. FIG. 47. Tan to light-brown breccia 21½ feet above the top of the Tymochtee in core 56–1. FIG. 48. Mottled gray dolomite 31½ feet above the top of the Tymochtee in core 56–4. FIG. 49. Tan to brown dolomite showing varying degrees of brecciation, 56 feet above the top of the Tymochtee in core 56–4.

beds in adjacent bedded strata. Carman made the following suggestion for the origin of the coarser breccias:

> . . . it is probable that the partly consolidated sediments were plowed up and broken up by great storm waves and that the fragments settled back with the interstices filled in with finer material. The whole mass was then compacted and cemented.



FIGURES 50–57. Polished sections of Raisin River Dolomite, X1. FIG. 50. Oolitic dolomite from East Sister Island. FIG. 51. Laminated light-brown dolomite from North Harbor Island. FIG. 52. Dolomite from the upper part of the middle unit on Hen Island showing lamination probably of algal origin. FIG. 53. Upper part of the Raisin River Dolomite from the north shore of the eastern peninsula of Middle Bass Island. The dark specks are gypsum. FIG. 54. Pseudobreccia from a mound along the north shore of the eastern peninsula of Middle Bass Island. FIG. 55. Breccia from a joint or solution channel in the uppermost Raisin River near the eastern tip of Middle Bass Island. Devonian sandstone forms the matrix. FIG. 56. Fractures in Silurian dolomite filled with Devonian sandstone, 76 feet above the top of the Tymochtee in core 56–4. FIG. 57. Breccia from a joint in the Raisin River Dolomite on East Sister Island. The coral fragments suggest that the clasts are at least partly post-Silurian.

This hypothesis constitutes a reasonable explanation for the more or less completely brecciated units in the Put-in-Bay Dolomite. However, it does not explain the channels cut into the Tymochtee, the discontinuous breccias of the upper Put-in-Bay and the Raisin River, nor the somewhat regular spacing and circular shape of many brecciated and pseudobrecciated zones when seen in plan view.

The evidence presented by the lowest part of the Put-in-Bay Dolomite suggests that, after bedded carbonates had accumulated to a thickness of 15 to 20 feet, regression of the seas permitted prolonged exposure and desiccation down to within a few feet of the Tymochtee, a horizon presently represented by the top of the lowest bedded unit in the Put-in-Bay. Carbonates above this horizon could have become broken into partially lithified blocks by the desiccation. Subsequent transgression would have exposed this clastic debris to severe wave action, as suggested by Carman, causing it to shift about over the cohesive substrate formed by the bedded material beneath. The fact that the lowest brecciated unit is continuous with breccias in channels cut down into the Tymochtee (fig. 34) indicates that the movement of this debris was locally channeled. Such channeled flow would provide the velocity necessary for erosion of the substrate. The channels may have initially been stream channels that were enlarged by seaward return of waters piled up during storms. They may also have acted as surge channels, controlling tidal flow as well as that related to storms.

The upper part of the Put-in-Bay (units 6 and 7 of Mohr) could represent a second cycle of transgression, regression, desiccation, and brecciation. These upper units are not as sharply differentiated as the lower, however, so the latter cycle may have been more complex.

Breccias and pseudobreccias in the Raisin River Dolomite were apparently formed by desiccation that was more limited, both horizontally and vertically, than that which occurred during Put-in-Bay sedimentation. Retreats of the sea were correspondingly of lesser magnitude and shorter duration. The somewhat regular horizontal spacing of these breccias and pseudobreccias indicates that desiccation proceeded outward from centers, the locations of which were probably controlled by shrinkage patterns. Such patterns may also have affected the desiccation of the Put-in-Bay, but would have been destroyed by the more complete brecciation. Once the centers of these brecciated and pseudobrecciated zones were established, the permeability resulting from desiccation would allow alternate soaking—by meteoric waters and/or hypersaline waters—and desiccation.

It appears that only the centers of the Raisin River breccias were ever dried out so completely that large clasts were produced, and dispersal of the clasts by wave action was limited. In the outer portions of the breccias, and in pseudobreccias such as those shown in Figures 39 and 54, the destruction of the original bedding probably resulted from solution and redeposition as well as from desiccation.

The upper part of the Bass Islands Formation is all dolomite, although much of it is calcareous. The rock is quite dense, and was very likely dolomitized before final lithification. Features indicative of shallow water and desiccation suggest that many of the original sediments were deposited in what was essentially a region of carbonate mud flats, analogous to that of the island of Bonaire, off the north coast of Venezuela, as described by Deffeyes, Lucia, and Weyl (1964). Here, evaporation over the flats produces brines that are enriched in magnesium as gypsum is precipitated. These brines move toward the open sea by seepage refluxion through recent carbonate sediments, which are being dolomitized. Refluxion of similar brines through the original upper Bass Islands carbonates toward the open sea to the southeast very likely caused similar dolomitization.

The Tippecanoe-Kaskaskia Unconformity

The top of the Silurian in the Findlay Arch region is the erosion surface which separates the Tippecanoe and Kaskaskia sequences as defined by Sloss (1963).

The angularity of this interregional unconformity is very low, but the hiatus involved is considerable.

In Ottawa County the erosion surface is not exposed, but it was examined in core 56–4 by the writer and in the core from the quarry on Marblehead Peninsula by Kerr (1950). In core 56–4 there is a pebble conglomerate near the top of the Silurian, and the top of the dolomite is cherty, porous, and calcareous, having the general appearance of a weathered surface. The uppermost 11 feet is fractured and brecciated. Below this is a 5-foot block tilted about 30 degrees, fractured normal to and parallel to the bedding. Similar fractures occur as low as 53 feet below the top of the Silurian. Calcite and celestite occur as fracture fillings and

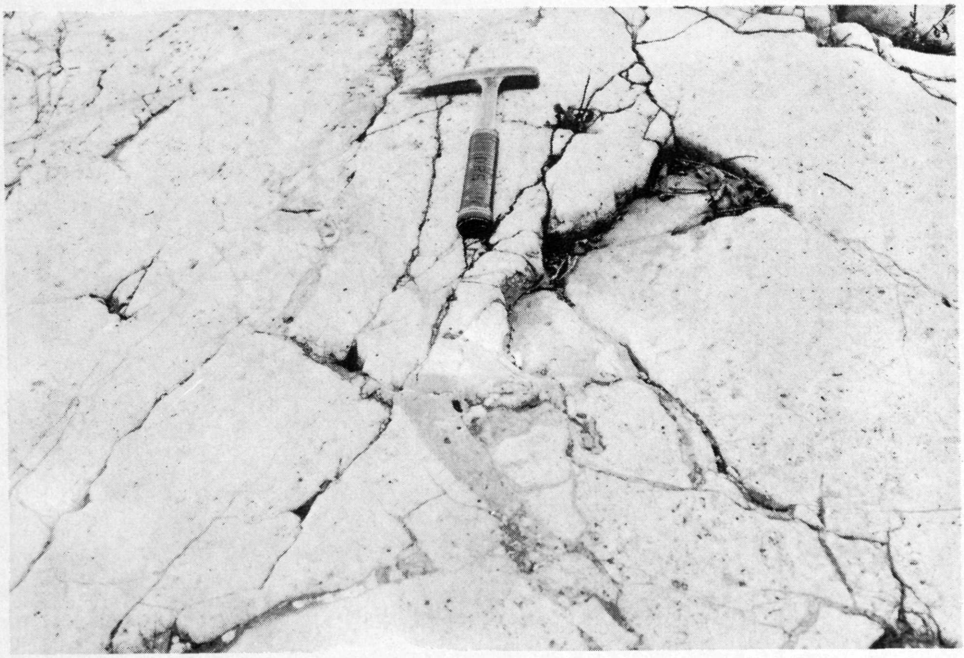


FIGURE 58. Sandstone filling fractures and solution channels in the Raisin River Dolomite along the north shore of the northeastern arm of Middle Bass Island.

as cavity fillings in breccias in the lower portion of the fractured zone. In the upper 26½ feet, the fractures are filled with dolomitic sandstone (fig. 56). Similar sandstone about one inch thick occurs immediately above the top of the Silurian. In the core from the Marblehead quarry, Kerr found sandstone occupying fractures as far as 14 feet below the top of the Silurian, with three inches of Devonian sandstone above that level.

A zone of fractures filled with sandstone can be seen along the north shore of the northeastern limb of Middle Bass Island (fig. 58). The fractures appear to be joints that developed during the post-Tippecanoe hiatus and that were in some cases enlarged by solution. Some of the larger ones contain breccias with a dolomitic sand matrix (fig. 55). The only other occurrence of post-Silurian breccia that was observed is on East Sister Island, where oolitic dolomite is cut by at least 2 large joints, over a foot across, filled with breccia. As seen in Figure 57, this breccia contains fragments of colonial corals, indicating that the breccia fragments are in part from normal-marine facies. This in turn suggests a post-Silurian age, possibly Helderbergian.

According to Sloss (1963, p. 99), complete emergence of the cratonic interior took place after Helderbergian time; regression from the Findlay Arch region may have begun much earlier. There is of course no way of telling how much material was removed by erosion.

By the end of the erosional interval, the type region of the Bass Islands Formation was probably an area of barren outcrops of dolomite, broken by joints and solution channels. Ground water draining from up-dip Tymochtee evaporites along the Findlay Arch at this time may have furnished the minerals now found in the lower fractures in core 56–4.

Sedimentation was not resumed until the region was invaded by transgressive marine seas in early Middle Devonian time. The dolomitic sand entrapped in the open spaces in the dolomite was probably washed into the area by this advancing sea.

ACKNOWLEDGMENTS

The writer is indebted to Robert L. Bates of Ohio State University for suggesting the study of Ottawa County and for conferring with the writer in the field. Charles H. Summerson of Ohio State conferred extensively with the writer in the field and made valuable suggestions with regard to sedimentary features of carbonate rocks. Special thanks are due to Richard Runvik, of the United States Gypsum Company, who furnished cores for study, as well as a large amount of information from company files. Field expenses were furnished by the United States Gypsum Company.

REFERENCES CITED

Adams, J. E. and **M. L. Rhodes.** 1960. Dolomitization by seepage refluxion. Amer. Assoc. Petroleum Geol. Bull. 44: 1912–1920.

Alling, H. L. and **L. I. Briggs.** 1961. Stratigraphy of Upper Silurian Cayugan evaporites. Amer. Assoc. Petroleum Geol. Bull. 45: 515–547.

Briggs, L. I. and **H. N. Pollack.** 1967. Digital model of evaporite sedimentation. Science 155: 453–456.

Carmen, J. E. 1927. The Monroe division of rocks in Ohio. Jour. Geology 35: 481–506.

———. 1946. The geologic interpretation of scenic features in Ohio. Ohio Jour. Sci. 46: 241–283.

Coash, J. R., R. J. Bernhagen, and **J. L. Forsyth.** 1957. Geology of the central lake plains area. *Ohio Acad. of Science, field conference in geology.* 13 p.

Deffeyes, K. S., F. J. Lucia, and **P. K. Weyl.** 1964. Dolomitization: observations on the island of Bonaire, Netherlands Antilles. Science 143: 678–679.

Ehlers, G. M. and **R. V. Kesling.** 1957. Silurian rocks of the Northern Peninsula of Michigan. Michigan Geol. Soc. Ann. Geol. Excurs. 63 p.

Evans, C. S. 1950. Underground hunting in the Silurian of south-western Ontario. Geol. Assoc. Canada Proceedings, 3: 55–85.

Gilbert, G. K. 1873. Geology of West Sister Island. Geol. Surv. Ohio, v. 1, pt. 1, Geology, p. 588–590.

Grabau, A. W. 1908. A revised classification of the North American Siluric System. Science, n. s. 27: 622–623.

——— and **W. H. Sherzer.** 1910. The Monroe formation of southern Michigan and adjoining regions. Michigan Geol. and Biol. Surv. Publ. 2, geol. ser. 1. 248 p.

Hall, J. 1839. New York Geol. Surv., Third Annual Report: 287–339.

———. 1852. Paleontology of New York, v. 2. 362 p.

Ham, W. E. 1962. Economic geology and petrology of gypsum and anhydrite in Blaine County. Oklahoma Geol. Surv. Bull. 89, Pt. II, p. 100–151.

Horvath, A. L. 1964. Stratigraphy of the Silurian rocks of southern Ohio and adjacent parts of West Virginia, Kentucky, and Indiana. Unpublished doctoral dissertation, Ohio State University. 155 p.

Janssens, A. 1968. Stratigraphy of Silurian and pre-Olentangy Devonian rocks of the South Birmingham Pool area, Erie and Lorain Counties, Ohio. Ohio Div. Geol. Surv. Rept. Inv. 70. 20 p.

Kerr, J. H. 1950. Stratigraphy and faunas of a core penetrating Middle Devonian and Upper Silurian formations of the Marblehead Peninsula, Ohio. Unpublished master's thesis, University of Michigan.

Landes, K. K. 1945. The Salina and Bass Island rocks in the Michigan Basin. U. S. Geol. Surv. Oil and Gas Invest., Prelim. Map 40.
Lane, A. C. 1895. The geology of Lower Michigan with reference to deep borings (edited from notes of C. E. Wright). Geol. Surv. Michigan, v. 5, pt. II. 100 p.
———, **C. S. Prosser, W. H. Sherzer,** and **A. W. Grabau.** 1909. Nomenclature and subdivision of the Upper Siluric strata of Michigan, Ohio, and western New York. Geol. Soc. Amer. Bull. 19: 553–556.
Liberty, B. A. and **T. E. Bolton.** 1956. Early Silurian stratigraphy of Ontario, Canada. Amer. Assoc. Petroleum Geol. Bull. 40: 162–173.
Logan, W. E. 1863. Geology of Canada; Canada Geol. Surv. Report of Progress to 1863. 983 p.
Miller, P. M. 1955. Stratigraphy and petrography of the Greenfield and Tymochtee formations of southern Ohio. Unpublished master's thesis, Ohio State University.
Mohr, E. B. 1931. The geology of the Bass Islands. Unpublished master's thesis, Ohio State University.
Murray, R. C. 1964. Origin and diagenesis of gypsum and anhydrite. Jour. Sed. Pet. 34: 512–523.
Napper, C. W. 1916. Occurrence of carbonaceous material in the Greenfield Member of the Monroe formation. Ohio Jour. Sci. 16: 155–159.
Newberry, J. S. 1870. Report of progress in 1869. Geol. Surv. Ohio, Part I, p. 1–51, map.
Orton, E. 1871. The geology of Highland County. Geol. Surv. Ohio, Report of Progress in 1870, Part III, p. 254–316.
———. 1888. The Trenton limestone as a source of oil and gas in Ohio. Geol. Surv. Ohio, v. 6, p. 101–310.
———. 1888a. Gypsum or land plaster in Ohio. Geol. Surv. Ohio, v. 6, p. 696–702.
Pinsak, A. P. and **R. H. Shaver.** 1964. The Silurian formations of northern Indiana. Indiana Geol. Surv. Bull. 32. 87 p.
Sherzer, W. H. and **A. W. Grabau.** 1909. Siluric fauna from southern Michigan. Geol. Soc. Amer. Bull. 19: 540–553.
Siegel, F. R. 1961. Factors influencing the precipitation of dolomitic carbonates. State Geol. Surv. Kansas Bull. 152, pt. 5, p. 127–158.
Sloss, L. L. 1963. Sequences in the cratonic interior of North America. Geol. Soc. Amer. Bull. 74: 93–114.
Sparling, D. R. 1965. Geology of Ottawa County, Ohio. Unpublished doctoral dissertation, Ohio State University. 265 p.
Stout, W. 1941. Dolomites and limestones of western Ohio. Geol. Surv. Ohio Bull. 42. 468 p.
Summerson, C. H. 1963. Itinerary, *in* Michigan Basin Geol. Soc. Guidebook, p. 13–45.
Swartz, C. K. 1942. Correlation of the Silurian formations of North America. Geol. Soc. Amer. Bull. 53: 533–538.
Textoris, D. A. and **A. V. Carozzi.** 1966. Stromatolite mound and associated facies, Ohio. Amer. Assoc. Petroleum Geol. Bull. 50: 1375–1388.
Ulteig, J. R. 1964. Upper Niagaran and Cayugan stratigraphy of northeastern Ohio and adjacent areas. Ohio Geol. Surv. Rept. Inv. 51. 48 p.
Verber, J. L. and **D. H. Stansbery.** 1953. Caves in the Lake Erie islands. Ohio Jour. Sci. 53: 358–362.
Williams, M. Y. 1919. The Silurian geology and faunas of Ontario Peninsula, and Manitoulin and adjacent islands. Geol. Surv. Canada Memoir 111. 195 p.
Winchell, N. H. 1873. Geology of Wyandot County. Geol. Surv. Ohio, v. 1, pt. 1, Geology, p. 625–639.
———. 1874. Report on the geology of Ottawa County. Geol. Surv. Ohio, v. 2, pt. 1, Geology, p. 227–235, map.